

# **Chemistry and Technology of Thermosetting Polymers in Construction Applications**

M.H. IRFAN



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## Preface

A large number of publications are available on paints and coatings, plastics and concrete. Unfortunately, the information available on polymeric construction products is scattered in journals, society reports and huge tomes which cover various technologies. This has tended to confuse and befuddle rather than enlighten the uninformed user. In this book an attempt has been made to present information on the chemistry of polymers, specific polymer systems in construction and health and safety issues.

Thermosetting polymers are those which 'set' irreversibly either in the presence of heat or by chemical reaction with a curing agent or additive, usually at ambient temperature. Products based on such polymers are widely used in the construction sector, and it seems certain that their use will spread, particularly in areas where there are extensive construction activities, such as the Middle East and South East Asia.

In this book I have confined discussion to those polymeric materials which are cured by chemical reaction and which have found widespread application in the construction industry. As such, the book covers materials based on epoxies, polyurethanes, silicones, polysulphides, alkyds and polyesters. In addition, there is a chapter on hybrid polymer systems and one on acrylics. It is true that acrylic emulsions are not strictly thermosetting polymer systems, but their widespread use and importance made their exclusion difficult. These materials find use as coatings, sealants, adhesives, grouts, flooring compounds, repair compounds and waterproofing agents.

The aim of the book is not to cover the chemistry of such systems in great detail, as this information can be found, if necessary, by consulting a range of other sources (some of which are listed in the references) but to provide specific, detailed information on the use of polymeric materials in the construction sector. As such, coverage of the important chemical details is confined to an introductory chapter, and the main chapters cover the uses of the specific materials, the technology of application and their strengths and weaknesses, as follows.

Chapter 2 covers the chemistry of polymers, keeping in view the chemistry involved in construction products. Chapters 3–9 detail specific polymer systems. Health and safety issues have also been covered in a general way. It is important to maintain that these general comments are for guidance only; any product should be used only in accordance with

the manufacturer's instructions. Before working with any of the materials, the manufacture's literature should be consulted for specific guidance on the risks involved in using the product and for details of any specific protective measures.

The chapters are arranged in order of volume of usage, and wherever possible standard specifications are presented. In addition, some useful testing standards are quoted in an appendix. This book will serve as a ready reference for those readers who are involved in the construction industry such as civil engineers, consultants, chemists and technical service personnel.

M.H. Irfan  
Jeddah



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# 1 Introduction

## 1.1 General discussion

Among the countless number of applications of polymers, the construction industry is one which utilises several polymeric materials. In this book I cover those polymeric materials which are single or bicomponent systems and are cured at ambient temperature either with the aid of curing agents or atmospheric moisture. The various polymers used in manufacturing such products include epoxies, polyurethanes, acrylics, silicones, polysulphides, alkyds and polyesters. As a result of innovation, new technologies exist which utilise more than one polymer in a single product. Such systems are discussed in Chapter 10, on hybrid polymers.

Manufacturing an end-product from the basic polymer involves the addition of several raw materials such as fillers, extenders, pigments, plasticisers, rheology modifiers, solvents, antifoaming agents, surface active agents, curing agents, light stabilisers, etc. Incorporation of these materials makes the end-product stable and cost-effective.

Ambient-cured products used in the construction sector to cater for a variety of end-uses are as follows:

- adhesives or bonding compounds;
- anchoring systems;
- crack injecting systems;
- grouts;
- industrial floorings;
- protective coatings;
- repair mortars;
- sealants;
- water repellents for masonry structures;
- waterproofing systems.

Table 1.1 mentions the various possibilities for various polymers. Before proceeding further, it is essential to have an understanding of the systems listed above.

Adhesives, non-scientifically, are materials which provide adhesion as a result of mechanical interlocking with the basic roughness of the adherend surfaces. A precise definition of an adhesive describes it as a substance capable of holding materials together by surface attachment.

**Table 1.1** Possible uses of various polymers within the construction industry

---

**Epoxies:**

Structural adhesives  
 General-purpose adhesives  
 Crack injecting systems  
 Anchoring systems  
 Grouts  
 Industrial flooring  
 Protective coatings  
 Repair mortars

**Polyurethanes:**

Construction sealants  
 Protective coatings  
 Industrial flooring  
 Adhesives for bonding wood  
 Waterproofing systems

**Acrylics:**

Caulking sealants  
 Anticarbonation coatings  
 Elastomeric coatings  
 Patch-repair mortars  
 General-purpose adhesives  
 Crack injecting systems

**Silicones:**

Masonry water repellents  
 Glazing sealants  
 Construction sealants  
 Sanitary sealants  
 High-temperature-resistant coatings

**Polysulphides:**

Fuel-, chemical- and solvent-resistant sealants  
 Construction sealants  
 Intumescent sealants  
 Coatings for secondary containments

**Alkyds:**

Decorative coatings

**Polyesters:**

Anchoring systems  
 Mortars for high initial strength  
 Coatings for sewage environment

---

The process of adhesion occurs as a result of intermolecular forces which hold the molecules together. Among various types, epoxies are among the most widely used polymer resins for structural adhesives. These thermosetting adhesives possess bonding properties characterised by a high strength/rigidity ratio and resistance to water, heat and mycological attack (Maslow, 1982). The suitability of adhesives by polymer type and materials adhered is given in Table 1.2.

**Table 1.2** Suitability of adhesives based on polymer type, by materials adhered

---

Epoxies:  
 asbestos-metal  
 concrete-concrete  
 metal-concrete  
 plastics (glass-reinforced)  
 plaster  
 concrete  
 tiles  
 wood  
 ceramics  
 glass  
 porcelain

Polyurethanes:  
 plywood

Acrylics:  
 wood  
 metal  
 plastic  
 ceramics

---

Anchoring systems are materials used mainly for securing bolts, bars, tendons or dowels in drilled or formed holes in concrete, masonry or natural rock. Polyester anchors are widely used because of their fast curing property and high early strength (Fosroc International, undated a). Epoxy anchors are applied in areas where there is a risk of alkaline hydrolysis.

Cracks occur in concrete structures for several reasons (ACI, 1993a; Concrete Society, 1982). The purpose of crack injecting systems is to fill in the cracks. Epoxy systems are a popular choice for non-moving cracks. In cracks where some movement is anticipated, polyurethane systems are used (Table 1.3).

Grouts are materials which permanently maintain the original level and alignment of machinery or equipment and transfer all loads to the foundation when shims and other temporary position devices are removed. A grout is a fluid material in an uncured state which subsequently hardens

**Table 1.3** Suitability of crack injecting systems

---

Epoxies:  
 Non-moving cracks as narrow as 0.05 mm

Polyurethanes:  
 Non-structural crack repair  
 Dry or damp conditions  
 Cracks where movement is anticipated

Acrylics:  
 Cracks where width is less than 0.3 mm (some systems are suitable for wet cracks)

---

to give specific physical properties. Epoxy-resin-based grouts form the principal material for cavity filling purposes. They have high impact and chemical resistance and are adhesives in their own right (ACI, 1993b; Fosroc International, undated b).

Polymeric overlays are used on concrete pavements to protect them from dust, excessive wear, cracking, crazing, spalling and to provide an attractive appearance. These materials are applied on concrete pavements in the form of screeds, self-levelling materials or floor coatings. Epoxies, polyurethanes and acrylics are commonly used, epoxies being the most commonly chosen. Table 1.4 gives the suitability of these materials for different environments.

Protective coatings are sequentially applied to an appropriately prepared surface to impart colour or to protect the surface. Table 1.5 lists the uses of various polymeric coatings. In general, coatings offer significant protection against the elements and enhance the appearance of the structure (Koleske, 1995).

Repair mortars are widely used for patching or repairing surface defects in many types of concrete structure (ACI, 1993c; Concrete Society, 1984). Epoxy mortars are adopted for large repairs owing to their negligible shrinkage; acrylate mortars are used for repairing small patches and where fast curing is required and polyester mortars are used for high initial strength.

In buildings the specific function of sealant is to prevent the passage of gases, liquids or solids and to protect concrete against damage. In tanks, canals, pipes and dams, joints are sealed to prevent the loss of contents. Fire-resistant joint sealing systems are used in high-rise buildings (ACI, 1990; SWRI, 1995). Table 1.6 lists the application areas of various sealants.

**Table 1.4** Suitability of polymeric floors

---

**Epoxies:**

Environments where chemical, abrasion and impact resistance is desired  
Can be applied on damp concrete  
Conductive floors provide effective control of static electricity  
Available in the form of screeds, self-levelling floors and floor coatings  
Water resistant

**Polyurethanes:**

Resistant to thermal shock, abrasion, impact and chemicals  
Some systems resist the attack of organic acids  
Available in the form of screeds and floor coatings  
Water resistant

**Acrylics:**

Properties are same as epoxy or polyurethane floors  
Suitable for dry environments

---

**Table 1.5** Suitability of various coatings

---

**Epoxies:**

interior applications  
tanks for drinking water  
metal surfaces and concrete  
corrosion and chemical resistant applications  
internal lining of pipes  
food industry applications  
sewage environments (epoxy tars)

**Polyurethanes:**

to protect concrete from de-icing salts  
to mask concrete discoloration  
to protect concrete from alkali-silica reaction  
weathering resistant applications  
for applications where elasticity must be unaffected by extreme climatic conditions

**Acrylics:**

to protect concrete substrates from chloride ions, carbonation, oxygen and water  
UV-resistant applications  
water vapour permeable applications  
where non-yellowing is required  
where excellent colour retention is required  
where elastomeric coatings are required to bridge smaller cracks

**Silicones:**

High-temperature-resistant applications

**Polysulphides:**

secondary containment coatings  
oil- and solvent-resistant applications

**Alkyds:**

UV-resistant applications  
decorative paints

**Polyesters:**

where resistance to acids is required  
sewage treatment plants

---

Waterproofing is normally used to prevent leakage of water into, through or out of concrete under hydrostatic pressure. If freezing and thawing conditions exist, or if water is carrying aggressive chemicals which attack reinforcing steel or concrete, then the waterproofing barrier will be used to prevent leakage into the concrete. A damp-proofing barrier system is used to perform the same function as a waterproofing system but cannot be used to protect against water under pressure (ACI, 1979). Liquid-applied polyurathane waterproofing systems are generally used in basements and roofs.

Epoxies and polyurethanes are widely used because several potentially interesting products can be created with them but not with other polymers. The same products formulated with different polymers find use in



**Table 1.6** Application areas of various sealants

Application area
Polyurethane: Building and construction joints
Acrylic: Non-moving joints such as door and window frames
Polysulphide: Oil and solvent related environments Building and construction joints
Acid-cured silicones: Structural glazing Sanitary sealants
Neutral cured silicones: Building and construction sealants Glazing sealants

specific applications. For example, epoxy mortars are suitable for large-volume repairs because of their negligible shrinkage, whereas mortars belonging to acrylate class are used for patch repairs where fast curing is desired. Epoxy flooring is resistant to many chemicals with the exception of organic acids; however, some types of polyurethane flooring resist the attack of organic acids.

Whereas epoxy crack injecting systems are applied in static cracks, polyurethane systems are suitable for cracks where some movement is anticipated. There are other applications where polymeric materials are considered as competitors to each other. For example, neutral cure silicone sealants and polyurethane sealants are both suitable for use in construction joints. The former type offers greater durability and ageing resistance. However, polyurethane sealants are widely used because of their cost-effectiveness. Furthermore, some products are preferred over their counterparts for environmental reasons.

## 1.2 Market review

Products based on polymers have penetrated the construction sector in industrially advanced countries, and there has been rapid growth in construction activities in Third World countries, involving a variety of specialised materials for diverse applications, where building codes are more 'progressive'. Companies are seeking to increase their market share by moving to the developing countries, where the economies are growing and there is huge potential for consumption per capita to increase.

To gain benefits of scale and access to a wider customer base many of the major companies have recently expanded. This has occurred either through acquisitions or through joint ventures. Here, local company knowledge and contacts combined with the high technological know-how and business acumen of the incoming partner are proving a winning formula. Strategic alliances are another way in which expertise is being combined to increase the market penetration of products.

The conditions and expectations of the market place are placing considerable demands on manufacturers. Environmental legislation calling for the replacement of volatile organic solvents (particularly in coatings) and the removal of hazardous chemicals, and increasing demands for more durable high-quality products, are leading to the development of new products. Research and development has a major role to play in the industry. New materials, modified chemistry, alternative solvents and new formulations and methods of application are becoming essential for survival in the marketplace. The factors driving new technology include volatile organic compound (VOC) compliance, availability of raw material and life-cycle analysis, price and performance.

## References

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## **2 Chemistry of polymers**

### **2.1 Introduction**

A polymer may be defined as a macromolecule formed by the chemical combination of identical units called monomers. The process by which polymers are formed is known as polymerisation. Polymerisation occurs via addition reaction or condensation reaction. The molecular weight of commercially important synthetic polymers is of the order of several thousands of daltons or higher. There are innumerable polymers used in countless applications. Polymer chemistry is a very wide subject, and innovations are continuously taking place. The aim of this chapter is not to discuss the generalities of polymer chemistry but to instil in the minds of readers some specific aspects of polymers used in the construction industry. These polymers include epoxies, polyurethanes, acrylics, silicones, polysulphides, alkyds and polyesters. Each polymer is discussed in a separate section covering only those aspects of chemistry which are related to construction industry products. Generalities of polymer chemistry and in-depth aspects of various polymers have been extensively covered by our pioneers in their publications. The lists of references and suggested readings given at the end of this chapter mention several useful publications for in-depth reading.

### **2.2 Epoxies**

Epoxy resins are compounds with more than one ethylene oxide group per molecule, commonly referred to as the epoxy group, 1,2-epoxides or oxirane. Such resins are categorised as 'thermosetting' since they are capable of 'curing' to form cross-linked networks. Epoxy resins are of particular interest to the plastics industry because of their polyfunctional character and their capacity to form addition products with a large number of substances without generating decomposition products (Ciba-Geigy, 1985).

Epoxy resins are not finished products but are reactive chemicals which are combined with other chemicals to give systems capable of conversion to predetermined thermoset products. Manufacturers of epoxy resins and hardeners do not supply finished compounds. Some specialised firms perform the task of compounding for several products.

Epoxy resins vary from low-viscosity liquids to high melting point solids. These variations are brought about by changing the ratio of epichlorohydrin and bisphenol A, used in their production (Doughar, 1974). Almost all the epoxy products used in the construction industry are based on liquid epoxy resins. These are ambient cured systems where cross-linking is achieved from self-polymerisation by the addition of curing agent (hardener). Stoichiometric ratios are necessary for epoxy curing agents. Selection of the proper curing agent for an application depends upon the viscosity of the mixture, the mass of the system and the temperature. It also depends upon the requirements of a cured system, such as resistance to chemicals, temperature and electrical properties.

The details of epoxy resin chemistry and various technologies are covered elsewhere (Lee and Nivelles, 1967; May, 1988; Oldring, 1996).

### 2.2.1 History

The history of epoxy resins begins in the early 1900s with the reported epoxidation of olefins. This technique was used only for the production of higher molecular weight mono-epoxy compounds. The technology was further explored only after the Second World War. Different contributions in the development of epoxies are outlined as follows (Lee and Nivelles, 1967, 1972; Sherman *et al.*, 1982).

- 1926: Eisleb noted the reaction of epichlorohydrin with secondary amines and subsequent dehydrogenation with caustic.
- 1927: Schrade cited the first commercial attempt to prepare resins from epichlorohydrin.
- 1930: Blumer described a composition which could be used in the manufacture of coatings, based on phenol aldehyde compounds reacted with epichlorohydrin.
- 1933: Schlack described a low molecular weight diglycidyl ether produced by the reaction from one mole of bisphenol A and ten moles of epichlorohydrin in a caustic medium.  
Stallman reported production of diglycidyl amines from ammonia and epichlorohydrin.
- 1934: Groll and Hearne obtained a variety of diepoxides from chlorinated alcohols.
- 1936: Caston produced a low-melting amber-coloured resin which was then reacted with phthalic anhydride to produce a thermoset compound.
- 1937: Unsuccessful attempts in Europe to employ epoxy resins in dental applications continued until 1939.
- 1939: Greenlee explored the epichlorohydrin-bisphenol A synthesis route for the production of new resins (without caustic-sensitive ester linkages) for coatings.

- 1943: Basic materials were patented as curing agents, but the applications were limited to dentistry.
- 1945: Ciba Ltd filed the first patent applications for epoxy adhesives.
- 1946: Ciba's products were offered commercially.
- 1956: Union Carbide developed cyclo-aliphatic epoxies via peracetic acid synthesis.
- 1960: Koppers Co. contributed *o*-cresol epoxidised novolacs.
- 1960s: Emphasis shifted to improving the quality of resins.
- 1970: Considerable research and development by Ciba-Geigy on hydantoins resulted in commercialisation of resins based on this heterocyclic moiety.
- 1976: Shell Chemical Co. introduced hydrogenated bisphenol A materials as ultraviolet (UV) weatherable systems to compete with polyurethanes.

Research is still ongoing in the quest for innovative technologies.

### 2.2.2 Commercial epoxy resins

**2.2.2.1 Bisphenol A resins.** The most widely used epoxy resins are diglycidyl ethers of bisphenol A (DGEBA). These are produced by the reaction of bisphenol A and epichlorohydrin in the presence of sodium hydroxide (Figure 2.1).

The bisphenol moiety offers outstanding properties such as toughness, rigidity and good high-temperature performance. Chemical resistance is provided by ether linkages; adhesive and reactive properties are imparted by the hydroxyl and epoxy groups.

Liquid undiluted bisphenol A based epoxy resins have average values of  $n$  less than 0.2 and viscosities ranging from approximately 7000–15 000 CP at 25°C.

A unique characteristic of bisphenol A epoxy resins is that as the number of repeating groups in the epoxy chain is increased the number of hydroxyl groups also increases while maintaining an epoxide functionality of two. Some hydroxyl functionality is essential to the performance of liquid epoxy resins. The concentration of the hydroxyl group influences reactivity, viscosity, pigment wetting, filler setting and thixotropy (Dow Chemical Company, undated a).

Resins having  $n$  values less than 1 are viscous liquids. The higher  $n$  value resins, particularly those with a molecular weight above 3000, are normally used in solution and find their application in heat-cured systems. In such resins the concentration of epoxy is low. They are cured with materials that react with hydroxyl groups along their backbone.

**2.2.2.2 Synthesis of DGEBA.** As mentioned above, bisphenol A and epichlorohydrin are the main raw materials in the manufacture of



DGEBA epoxy resins. Two moles of epichlorohydrin are theoretically required for each mole of bisphenol A. However, this ratio gives less than 10% yield practically. Therefore excess of epichlorohydrin is used by doubling or tripling the amount to achieve greater than 90% yields. The process involves the following stages (Lee and Nivelles, 1972):

1. the required quantities of epichlorohydrin and bisphenol A are charged into the reactor and mixed thoroughly by an agitator;
2. the above solution is heated at 99°C–102°C in the presence of 40% sodium hydroxide solution for about 3½ h;
3. during the reaction process, water is distilled as an azeotrope with epichlorohydrin; the latter is returned to the reaction mixture after the separation of water;
4. after 15 min (at the reaction temperature), water is removed and residual epichlorohydrin is recovered by distillation, first at 150°C and then at 200°C and 2 mm Hg pressure;
5. toluene or methylethyl ketone (Kumar and Kumar, 1982; Lee and Nivelles, 1972) is added in order to separate the sodium chloride formed during the reaction, followed by filtration and distillation to remove the solvent. The resins obtained from this process give a yield of 90–95%.

The molecular weight of the resulting resins will depend upon the ratio of epichlorohydrin to bisphenol A employed. The greater the quality of epichlorohydrin, the lower the molecular weight of the resulting resins. (Lee and Nivelles, 1967). Commercial epoxy resins, predominately DGEBA, are available in several molecular weight ranges and some are composed of a mixture of more than one type of epoxy resin (e.g. blends of bisphenol A and bisphenol F based resins); additionally, they may contain modifiers and diluents. Table 2.1 describes the properties of commercial liquid epoxy resins, as taken from the technical literature of several epoxy manufactures.

**Table 2.1** Physical properties of several commercial liquid epoxy resins

Epoxy equivalent weight	Viscosity (mPas at 25°C) <sup>a</sup>	Density (gm/ml/at 20°C) <sup>b</sup>	Colour number (Gardener)	Bisphenol type
180	8500 ± 1500	1.16	≤ 2	A
186–190	11 000–14 000	1.17	≤ 3	A
172–185	6500–8000	1.17	≤ 3	A/F blend
180	7000 ± 1500	1.17	≤ 2	A/F blend
192	16 000 ± 3000	1.17	≤ 2	A

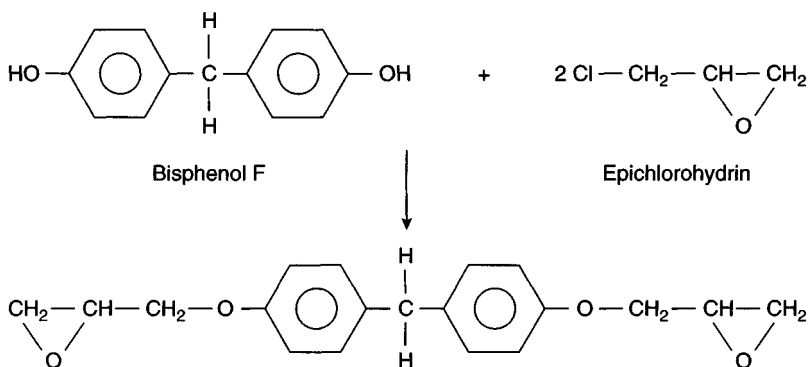
<sup>a</sup> Values for DIN 5215.

<sup>b</sup> Values for DIN 51757.

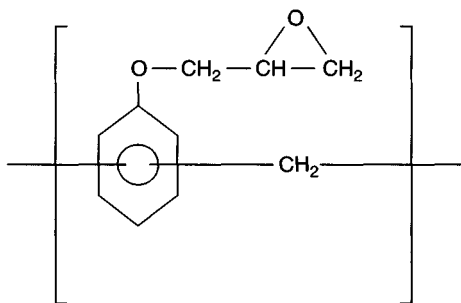
**2.2.2.3 Bisphenol F based epoxy resins.** Instead of reacting bisphenol A with epichlorohydrin to form a liquid resin, a similar reaction can be conducted with bisphenol F (Figure 2.2). Bisphenol F is composed of a mixture of isomers – *ortho-ortho*, *ortho-para* and *para-para* linkages – whereas bisphenol A is composed mainly of *para-para* linkages. If  $n$  is less than about 0.2, the resins are called bisphenol F epoxides. If  $n$  is higher they are referred to as epoxy phenol novolac (EPN) resins (Helfad, 1996).

The repeat unit of bisphenol F epoxy resins (Figure 2.3) or epoxy novolac resin does not significantly increase the epoxy equivalent weight although viscosity and functionality do increase (Helfad, 1996).

Bisphenol F epoxy resins provide similar chemical resistance to that of bisphenol A based epoxies. However, there is some improvement to acid resistance in the former, depending on the curing agent used. With bisphenol F epoxy resins it is possible to have higher filler levels and faster bubble release because of their relatively low viscosity (Figure 2.4).

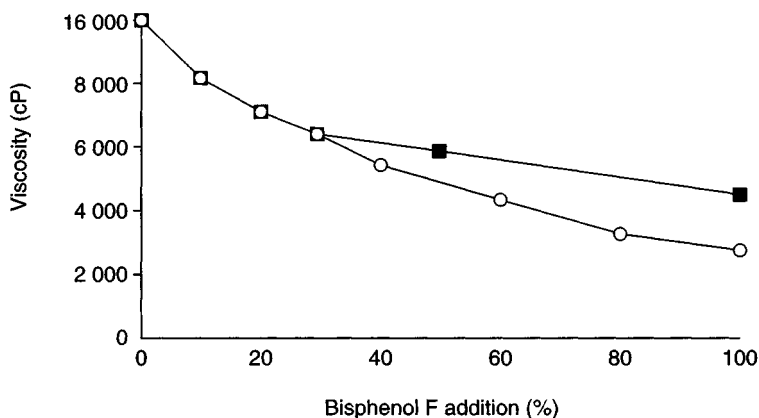


**Figure 2.2** The synthesis of a bisphenol F based epoxy resin



**Figure 2.3** Repeat unit of bisphenol F epoxy resin





**Figure 2.4** The viscosity of bisphenol F/bisphenol A blends. ■ = DER 354; ○ = DER 354LV. DER is the registered trademark of Dow Epoxy Resins. Reproduced with permission from the Dow Chemical Company, Midland, MI, USA

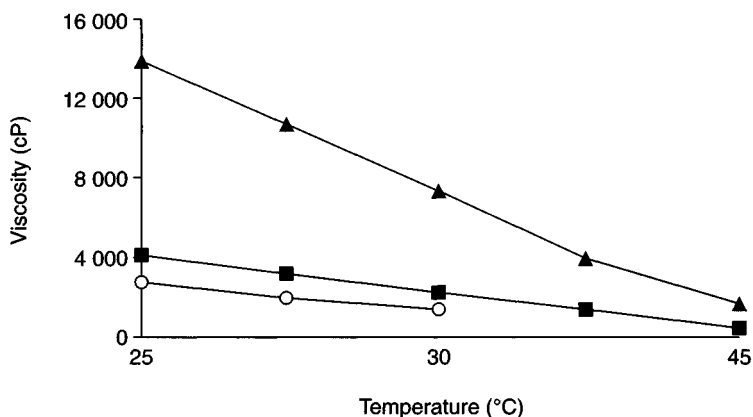
**2.2.2.4 Bisphenol A/bisphenol F epoxy resin blends.** It is possible to use blends of bisphenol A and F to achieve superior properties. Many such combinations are commercially available. Such blends significantly reduce the crystallisation tendency which may occur with bisphenol A based epoxy resins when they are subjected to temperature cycling. Such blends also facilitate filler loading and processability.

## 2.2.3 Properties of uncured epoxy resins

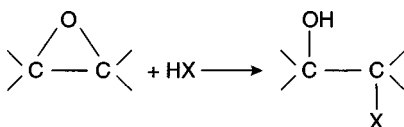
**2.2.3.1 Viscosity.** The viscosity of epoxy resins depends on temperature and molecular weight. An increase in temperature reduces the viscosity. The presence of high molecular weight species increases the viscosity (Figure 2.5).

**2.2.3.2 Epoxide equivalent weight.** The epoxide (or epoxy) equivalent weight (EEW) is defined as the weight in grammes of resin containing one gramme equivalent of epoxy. The 'epoxy value' represents the fractional number of epoxy groups contained in 100 g resin. Division of the epoxy value by 100 g gives the epoxide equivalent. The EEW is commonly determined by addition of hydrogen halide to the epoxy group (Figure 2.6).

The difference between the amount of acid added and the amount unconsumed, determined by titration with a standard base, is converted to the epoxide equivalent (Lee and Nivelles, 1972). Complete procedures of determining the EEW are given elsewhere (Lee and Nivelles, 1967). The EEW is the most important characteristic of bisphenol A epoxy resin.



**Figure 2.5** Plot of epoxy resin viscosity against temperature.  $\blacktriangle$  = DER 331;  $\blacksquare$  = DER 354;  $\circ$  = DER 354LV. DER is the registered trademark of Dow Epoxy Resins. Reproduced with permission from the Dow Chemical Company, Midland, MI, USA



**Figure 2.6** The addition of hydrogen halide to the epoxy group

It is equal to half the molecular weight; for example, if the EEW is 170, the molecular weight is 340.

**2.2.3.3 Hydroxyl equivalent.** The hydroxyl equivalent is the weight of epoxy resin containing one equivalent of hydroxyl group. It is important in calculating average molecular weights. It is determined by various methods (Lee and Nivelles, 1967), such as esterification with acids, reaction with lithium aluminium hydride, reaction with acetyl chloride and near-infra-red spectroscopy.

**2.2.3.4 Iodine number.** The iodine number is the number of milligrammes of iodine absorbed by one gramme of the compound. It is a measure of the unsaturation of the epoxy molecule.

**2.2.3.5 Colour.** The colour of epoxy resins is normally expressed in Gardner colour units, Gardner 1–5 are pale straw colours, Gardner 5–12 are significantly yellow, Gardner 12+ are darker coloured (but translucent).

**2.2.3.6 Structure.** The structure of the resin is a determining factor for the physical and chemical properties. The number and location of the reactive sites determines the functionality and the cross-linking density.

#### 2.2.4 Curing agents (hardeners)

Curing agents or hardeners are chemically active compounds which convert epoxy resins into hard, infusible thermosets. They promote the cross-linking reaction either by polyaddition or by homopolymerisation. The curing reaction occurs without the formation of any by-product.

In polyaddition, cross-linking occurs by means of chain extension. The majority of ambient-cured construction products are based on this type of reaction, where *in situ* polymerisation occurs after the epoxy resin base and the curing agent are mixed. The curing agent causes the epoxide or hydroxyl groups to react (Ellis, 1994).

A wide range of curing agents are available to cure liquid epoxy resins under ambient conditions. However, relative humidities up to 100% and temperatures below 0°C may be encountered on building sites. It is unusual for a single curing agent type to provide optimum characteristics in all respects; therefore, selection is made according to the priorities of the application and the performance requirements. Besides affecting the viscosity and reactivity of the formulation, curing agents determine both the types of chemical bonds formed and the degree of cross-linking. These in turn affect the chemical resistance, electrical properties and heat resistance of the cured formulation (Dow Chemical Company, undated b). Commonly used epoxy curing agents in construction products will be discussed in this section. A summary of the agents discussed is given in Tables 2.2 and 2.3.

**2.2.4.1 Aliphatic polyamines.** These are low-viscosity materials with high reactivity and fast cure at ambient temperatures. The basic reaction of aliphatic amines with epoxy resin is shown in Figure 2.7.

Polyamine-cured epoxy systems have reasonable colour and colour retention, improved physical properties and good chemical resistance. They are, however, moisture sensitive, relatively toxic and have poor resistance to organic acids. Examples of this class are diethylene triamine (DETA) and triethylene tetramine (TETA).

Aliphatic amines are used principally in civil engineering applications such as in patch repair systems, adhesives, floorings, high solid coatings and grouts.

**2.2.4.2 Cycloaliphatic amines.** Cycloaliphatic amines possess an amine functionality located on a carbon atom ring, and contain no unsaturation. Common examples of cycloaliphatic amines are shown in Figure 2.8.

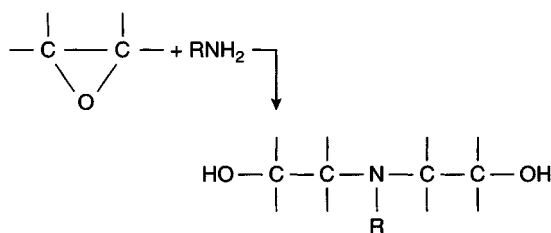
**Table 2.2** Curing agent types: typical properties and applications. Source: Air Products (Chemicals) plc, Clayton, Manchester, UK

Product group	Principal properties	Principal applications
Aliphatic amines	Wide range of products with differing properties; high reactivity, fast cure at ambient temperatures; relatively moisture-insensitive; reasonable colour and colour retention; good chemical resistance, particularly to solvents	Civil engineering, e.g. patch repair systems, flooring, adhesives; high solids coatings; certain grades used as cost or performance alternatives to cycloaliphatics; accelerators for other amine curing agents
Cycloaliphatic amines	Cure at low temperatures under damp conditions; good film properties (e.g. excellent gloss); excellent colour and colour stability; good adhesion and very good chemical resistance; range of cure times and pot-lives	Solvent-free and solventless coatings, self-levelling and screed floors; tile grouts; adhesives
Aromatic amines	Product range with variable pot-life and curing cycle; cure under high humidity and low temperature; high gloss, bloom-free films with excellent chemical resistance; dark colour	Solvent-free coatings, e.g. for edible-oil, beer and wine tanks and chemical and oil tanks; epoxy coal tar coatings; chemical-resistant flooring
Amidoamines	Range of amidoamines of differing reactivities; low viscosity; exhibit very good adhesion, particularly to concrete; good cure under humid conditions; generally poor chemical resistance	Civil engineering, e.g. concrete bonding, crack injection, screed floors, etc.; coatings, e.g. as modifiers to cycloaliphatic and/or aliphatic curing agents; adhesives
Solid adducts	Isolated amine products, in particular, offer advantages such as low colour, low free amine content and low irritation potential; they also provide non-yellowing, bloom-free films with good chemical and solvent resistance	Amine adducts: solvent-based, two-pack coatings, e.g. primers, finishes and coal tar epoxy coatings
Polyamides	Polyamides offer ambient cure, low toxicity, good flexibility and toughness, with high viscosity, long pot-life and good water and corrosion resistance; polyamide adducts provide good compatibility (without induction period) and better cure under adverse conditions than do standard polyamides	Polyamides: solvent-based, two-pack coatings, e.g. primers and finishes; epoxy coal tar coatings, adhesives, putties and sealants
Water-dispersible	Low viscosity; low odour; non-flammable; easy to clean; good adhesion, especially to damp concrete; good abrasion resistance	Primarily concrete coatings, e.g. food factories, show-rooms, laboratories, hospitals, nuclear power stations, breweries, etc.; adhesives

**Table 2.3** Curing agents for epoxies – comparison summary. Source: Air Products (Chemicals) plc, Clayton, Manchester, UK.

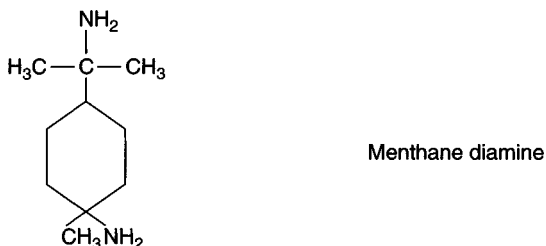
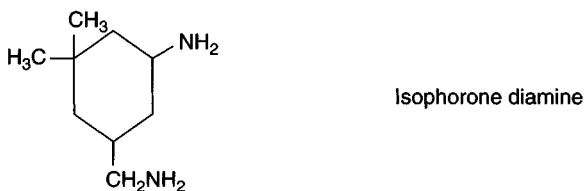
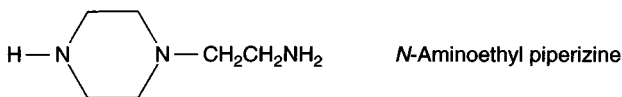
Colour and colour stability	Viscosity	Pot life	Low temp-ature cure	Surface film look	Film flexibility	Adhesion	Chemical resistance		
							Acids	Solvents	Water
Excellent	Low	Long	Good	Gloss	Excellent	Excellent	Excellent	Very good	Excellent
3	4	(5)	7	5	1	1	5	6	1
	3		5	4				7	
		2				2			
6					2		3		2
						4			
4	2	1	4	3	3		4	3	
		6		7				4	3
7			3		4	7	6		4
	5								
		(5)	6	1			7	5	
	6					3			
2					5				6
	7	4							
1			1	2			2	1	7
		6				6			
					6				
5	1	7	2	6	7	5	1	2	5
Poor	High	Short	Poor	Grease	Fair	Moderate	Fair	Poor	Very good

Note: 1 = polyamide, Ancamide 350A; 2 = amidoamine, Ancamide 506; 3 = cycloaliphatic-A, Ancamine 1618; 4 = cycloaliphatic-MB, Ancamine MCA; 5 = aromatic, Ancamine TL/TLS; 6 = aliphatic-A, Ancamine 1608; 7 = aliphatic-MB, Ancamine 1856; A = adduct-type; MB = Mannich-base-type.

**Figure 2.7** The basic reaction of the epoxy group with aliphatic amines

Suitable modifications are made in commercial products to rectify the associated problems, for example the water sensitivity, tendency to carbonate and inability to give complete cure at room temperature.

Owing to the absence of unsaturation, cycloaliphatic amines provide high weatherability and high resistance to yellowing under heat. Cycloaliphatic amines can cure even under damp conditions. The cured system exhibits excellent gloss, excellent colour and colour stability, good

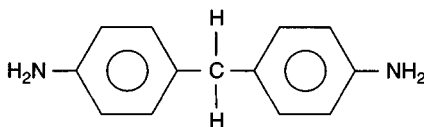


**Figure 2.8** Some cycloaliphatic amines

adhesion and very good chemical resistance. A range of cure times and pot-lives are possible. Applications include solvent-free and solventless coatings, self-levelling and screed floors, tile grouts and adhesives. They are particularly suited to areas where aesthetic considerations are important.

**2.2.4.3 Aromatic amines.** Aromatic amines are usually solids. Owing to their slow reactivity in room temperature some modifications are essential when they are to be used as curing agents for epoxies, in civil engineering applications. Liquid versions are available under proprietary designations, consisting of eutectic blends, adducts or diluent-containing materials. The most commonly used aromatic amine is methylene dianiline (MDA), shown in Figure 2.9.

Depending upon the modification, it is possible to have a product range with variable pot-lives and curing cycles. The longer pot-life versions are



**Figure 2.9** Methylene dianiline

of particular use for applications in tropical conditions. Modified aromatic amines can cure under high-humidity and low-temperature conditions, giving high-gloss, bloom-free films and excellent chemical resistance.

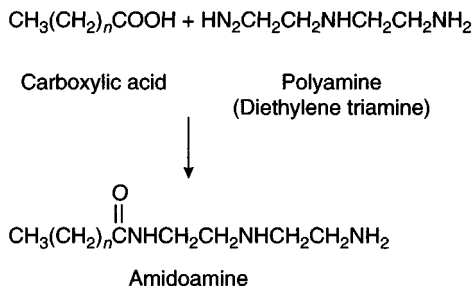
Aromatic amines are useful curing agents for solvent-free coatings, epoxy coal tar coatings, chemical resistant floorings, etc. The major disadvantage of aromatic amines is their poor colour and poor colour retention. Aromatic amines have been found to carry the risk phrase "R 45 'may cause cancer'" (Hunt and Ashcroft, 1994). Legislation is being imposed in many countries, and research is in progress to find a suitable replacement. The use of aromatic amines has been confined to a last-resort, where no other curing agent is suitable.

Cycloaliphatic and polycycloaliphatic polyamines are finding increasing use as non-toxic replacements. Polycycloaliphatics have shown outstanding mechanical properties, high acid and solvent resistance and similar adhesion compared with standard plasticised aromatic amines (Hunt and Ashcroft, 1994).

**2.2.4.4 Amidoamines.** Amidoamines are low-viscosity, amber-coloured fluids. They are formed by the reaction of a monobasic carboxylic acid ( $C_{16}$ – $C_{19}$ ) with an aliphatic amine, for example DETA or TETA (Figure 2.10). With these substances cure is achieved by the amine functionality present but not by the amide group. The free primary and secondary amine groups are the reactive sites.

The advantages of amidoamines are reduced volatility, convenient mix ratios, good flexibility and toughness. The disadvantages are poor performance at elevated temperatures, and less chemical resistance compared with other amines. Water resistance may be unsatisfactory for long-term structural applications (Mays and Hutchison, 1982).

Major construction applications include adhesives, concrete bonding compounds, crack injections and screed floors. They are also finding use as modifiers to cycloaliphatic and aliphatic amine curing agents (Air Products, undated).



**Figure 2.10** The synthesis of an amidoamine

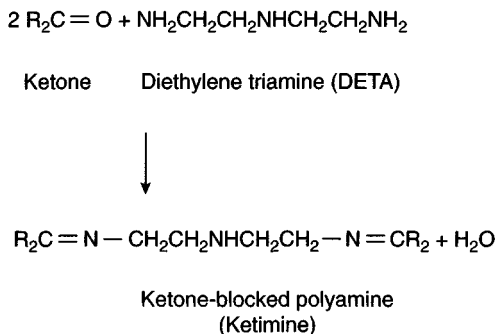
**2.2.4.5 Polyamides.** Polyamides are formed by the condensation reaction of polyamines with dimeric fatty acids. They are available from a number of suppliers in a large variety of viscosities and molecular weights. Many products are available in the form of adducts which provide good compatibility with epoxy resins without the need for an induction period and give a better cure under adverse conditions compared with standard polyamides. Polyamide curing agents offer a number of desirable features, as follows (Dow Chemical Company, undated b):

- low toxicity;
- good flexibility and toughness;
- good adhesion;
- moisture resistance;
- convenient mixing ratios.

They are used mainly as curing agents for solvent-based coatings, epoxy coal tar coatings, putties, adhesives and solvents. Polyamide-cured epoxy coatings have the drawback of being somewhat softer and less chemically resistant than other coatings.

**2.2.4.6 Ketone-blocked polyamines.** These curing agents are complexes of primary aliphatic polyamines with ketone solvents (Figure 2.11). They are also called 'ketimines'. When mixed with the DGEBA they provide long pot lives (up to 8 h) at room temperature.

The curing reaction occurs by the dissociation of the complex by atmospheric moisture in which the ketone evaporates and the primary amines provide cure. Ketimines are employed as curing agents in coatings containing 100% solids.



**Figure 2.11** The synthesis of a ketone-blocked polyamine (ketimine)



**2.2.4.7 Polysulphides.** Polysulphides are used as curing agents for epoxies in the presence of tertiary amines which accelerate the cure; such cured systems exhibit good flexibility and tensile strength at ambient temperature. In a real sense they are flexibilisers for epoxy systems. Specific applications are for the crack injection system (for moving cracks) and coatings (Chapter 10).

**2.2.4.8 Water-dispersible curing agents.** With these curing agents it is possible to have a water-soluble compound in an epoxy system to obtain maximum possible resistance to corrosion and humidity. Some curing agents from this category emulsify liquid epoxy resins in water, making the entire system dilutable with water. More explanations are given in section 3.12 of water-borne epoxy systems.

**2.2.4.9 Homopolymerisation.** Homopolymerisation occurs in the presence of Lewis acids or tertiary amines. It may be either cationic or anionic. This reaction does not have any significance for ambient-cured multi-component epoxy products for use in construction.

## 2.2.5 *Calculation of mixing ratios of epoxy resins and amine curing agents*

For amine curing agents which are recommended for use in stoichiometric quantities with epoxy resins the following guidelines apply:

1. If an active hydrogen equivalent weight is quoted for the amine, then the parts by weight (pbw) of amine per 100 pbw resin is given as the active hydrogen equivalent weight multiplied by 100 and divided by the epoxide equivalent weight of the resin.
2. If the molecular weight of the amine is quoted, calculate the active hydrogen equivalent weight as the molecular weight of the amine, divided by the number of active hydrogens, then proceed as in point 1.
3. If a quantity per gramme mole of epoxy resin is quoted the pbw of amine per 100 pbw resin is the quantity per gramme mole multiplied by 100 and divided by the epoxide equivalent weight of the resin.
4. If a ratio with another epoxy resin is quoted, for example if resin B is 100 pbw, and the hardener is 60 pbw, the pbw of hardener per 100 pbw of epoxy resin A is the quantity per 100 pbw of resin B (in pbw) multiplied by the epoxide content of resin A (in mol/kg), divided by the epoxide content of resin B (in mol/kg). Hence, if resin A has an epoxide content of 3.2 mol/kg, and resin B has an epoxide content of 5.4 mol/kg, then the weight of hardener per 100 pbw of resin A is  $[(60 \times 3.2)/5.4]$  pbw = 35.6 pbw.

### 2.2.6 Additives for epoxy formulations

Pure epoxy resins, so-called basic resins, are unsuited to building applications because of their high viscosity. Modifications are necessary to achieve the required viscosity, wettability, carbonate resistance, curing rate, cost reduction and numerous other properties. However, the modifiers must be chosen so as not to impair the other valuable attributes of the epoxy resins. For example volatile solvents are unsuitable for thick coatings, because any solvent retained in the cured system will reduce the mechanical and thermal properties and the corrosion resistance. The specific property needs for a particular application may be tailored to each system to maximise the remarkable potential of epoxy resins (Dow Chemical Company, undated c).

**2.2.6.1 Plasticisers and flexibilisers.** Plasticisers are long-chain molecules placed into the structure which remain unreacted after cure, whereas flexibilisers are long-chain elements placed into the epoxy system which do react during cure. The purpose of employing a flexibiliser or plasticiser is to provide resilience and toughness to a rigid system in order to improve the thermal shock and impact resistance and to increase flexibility. Dibutyl phthalate is a commonly used plasticiser. However, in 1994 it was reclassified as toxic to humans, with possible risks of impairing fertility and harming the unborn child. A search for alternative sources of plasticiser to dibutyl phthalate is in progress and a friendly material is expected in the near future.

Examples of other plasticisers are an adduct of tetrahydrofurfural alcohol and ethylene oxide and the reaction products of ethylene glycol either with organic acids or with anhydrides. Polyols and natural and synthetic rubbers are examples of flexibilisers.

**2.2.6.2 Resinous modifiers.** Epoxy resins have the ability to interact with other resins to form heteropolymers. These are also known as plastic alloys. Improved properties can be achieved with modified systems which are otherwise not possible with a single resin; for example epoxies can form plastic alloys with poly(vinyl formal) to improve the impact resistance and peel strength of adhesive formulations.

Epoxy resins form alloys with a number of other resins such as polysulphides, polyurethanes, fluorocarbons, silicones, furfural resins and acrylic resins.

**2.2.6.3 Pigments.** The colourants for epoxies can be classed into dyes and pigments. The materials may be either organic or inorganic, the organic materials being preferred for their brightness and strength (Lee and Nivelle, 1967).

The best pigment to achieve a given colour will depend on the type of curing system employed and the environmental conditions to which the cured system will be exposed.

**2.2.6.4 Fillers.** Fillers are added in epoxy formulations to obtain the desired properties in a system. Additionally, they reduce the cost of formulations. The amount of filler by weight that can be incorporated into an epoxy resin will depend on the filler's particle size, density and oil absorption properties. Within each family of filler there are products that impart different properties because of varying coarseness, impurity level and method of preparation. The effect of addition of fillers to epoxy formulations is to:

- improve thixotropy;
- increase the pot-life and lower the exotherm;
- reduce the tensile and flexural strength;
- reduce the shrinkage;
- improve the compressive strength;
- increase the surface hardness;
- increase the thermal conductivity, in the case of fibrous metallic fillers;
- lower the coefficient of thermal expansion;
- increase the thermal shock and impact resistance;
- bring, perhaps, a marginal increase or decrease in chemical resistance (depending upon the type of filler);
- increase, perhaps, the machinability and abrasion resistance, making the system harder;
- provide good electrical conductivity.

Commonly used fillers for epoxy systems are calcium carbonate, micas, silica, clays, powdered metals, talc, wood flour, aluminium silicate etc. The properties imparted by fillers to an epoxy system are given in Table 2.4 (Dow Chemical Company, undated d).

**2.2.6.5 Reactive diluents.** In epoxy resin chemistry, the term 'reactive diluent' refers to compounds which, by virtue of their constituent groups,

**Table 2.4** Some properties imparted by fillers to an epoxy system

Filler	Property
Calcium Carbonate, Calcium Silicate, Powdered Aluminium, Copper	Improved Thermal Conductivity
Alumina, Flint Powder, Carborundum, Silica, Molybdenum Disulphide	Improved Machinability
Chopped Glass	Improved Abrasion Resistance
Mica, Silica, Powdered or flaked Glass	Improved Impact Strength
Metallic Filler or Alumina	Improved Electrical Conductivity
Colloidal Silica, Bentonite Clay	Improved Thixotropic Response

participate in the cross-linking reaction between resin and hardener and become chemically linked into the cured system. This includes only those compounds which have a lower molecular weight than the epoxy resin itself, possess a lower viscosity, contain at least one epoxide group per molecule and which are completely compatible with epoxy resins.

In addition, a good reactive diluent will have favourable physiological properties, low vapour pressure, a very good thinning effect and little influence on the thermal, mechanical and electrical properties of the epoxy in the cured state. In most cases, reactive diluents are monoglycidyl, diglycidyl or polyglycidyl ethers, glycidyl esters with an aromatic or aliphatic structure or epoxidised unsaturated compounds. Reactive diluents having a low vapour pressure and high LD<sub>50</sub> value should be employed. In all cases, as a general precaution, skin contact with reactive diluents should be avoided. In the building sector, the linear coefficient of expansion – which varies according to the reactive diluent used – can be important. A general classification of reactive diluents is given in Table 2.5.

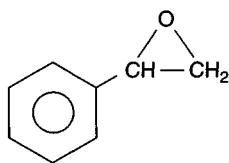
**2.2.6.5.1 Monoepoxy reactive diluents.** Monoepoxy diluents contain single epoxy functionality without reactive sites. They reduce the functionality of the system and its cross-linking density. They are thus regarded as ‘chain stoppers’. Monoepoxy diluents are generally employed to improve the wetting ability of the systems (Figure 2.12) (Lee and Nivelles, 1967).

**2.2.6.5.2 Diepoxy and polyepoxy reactive diluents.** Diepoxy or polyepoxy reactive diluents are incorporated in order to preserve physical properties at elevated temperatures. These diluents will not reduce system functionality and in some cases will result in an increase in system cross-linking density. They can be used in higher concentrations than can the monoepoxy diluents to obtain the desired reduction in viscosity. Some examples are shown in Figure 2.13.

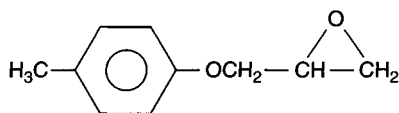
**2.2.6.5.3 Non-epoxy-containing reactive diluents.** The reactive non-epoxy diluents consist of co-curing agents, unsaturated molecules, active hydrogen-containing molecules, materials which are capable of promoting

**Table 2.5** Reactive diluents for epoxies, by functionality and nature

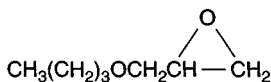
Monofunctional, aromatic: cresyl-glycidyl ether <i>p</i> -tertiary butylphenyl glycidyl ether	Difunctional, aliphatic: butane diol-diglycidyl ether cyclohexane dimethanol diglycidyl ether
Monofunctional, aliphatic: ethyl hexyl-glycidyl ether long-chain aliphatic glycidyl ethers	hexane-diol diglycidyl ether polyoxypropylene diglycidyl ether
	Trifunctional, aliphatic: polyoxypropylene triglycidyl ether



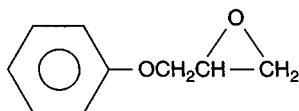
Styrene oxide (120)



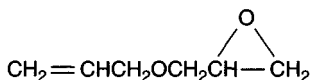
Cresyl glycidyl ether (150)



Butyl glycidyl ether (130)



Phenyl glycidyl ether (150)



Allyl glycidyl ether (114)

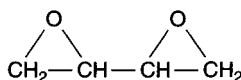
**Figure 2.12** Monoepoxy diluents. Molecular weights are shown in parentheses

transesterification with available hydroxyl groups and materials capable of reacting with the curing agent. They influence the cross-linking density and system functionality and in general effect other properties. Examples of such diluents are tertiary amines, short-chain polyols, E-caprolactum and lactones.

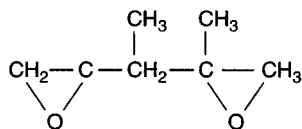
**2.2.6.6 Non-reactive diluents.** These diluents are low-viscosity materials which do not have any reactive sites and thus do not react with the epoxy systems. These diluents generally impart flexibility and improve the impact resistance, giving better thermal mechanical shock resistance. However, there is a sacrifice in physical strength, chemical resistance and high-temperature performance. Addition of 30 parts non-reactive diluent to 100 parts epoxy resin usually does not affect the physical properties of the system. Commonly used non-reactive diluents are nonyl phenol, furfuryl alcohol and dibutyl phthalate.

**2.2.6.7 Solvents.** Solvents are employed to ensure good application properties. Commonly used solvents are alcohols, aromatic naphthas, esters, glycol ethers, ketones, toluene and xylene.

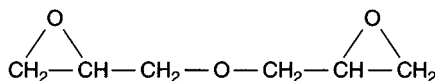
High molecular weight solvents are not suitable for epoxy systems as they become entrapped in the film and affect the properties. Also, solvents are not used which react with the curing agents; for example ester



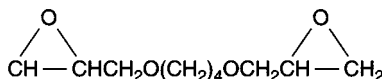
Butane oxide (86)



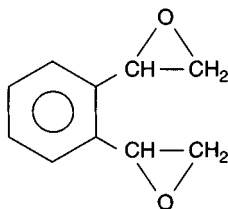
Dimethyl pentane dioxide (128)



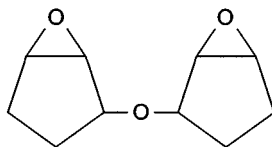
Diglycidyl ether (130)



Butane diol diglycidyl ether (202)



Divinyl benzene dioxide (162)



Bis (2,3-epoxycyclopentyl) ether (182)

**Figure 2.13** Diepoxy and polyepoxy reactive diluents. Molecular weights are shown in parentheses

solvents have a tendency to react with amine and inhibit the resin curing process (John, 1974).

**2.2.6.8 Accelerators for epoxy systems.** Accelerators shorten the gel time and increase the curing rate. Accelerators are employed based on the curing agent.

**2.2.6.8.1 Acidic accelerators.** Acidic accelerators are used with amines, amido amines and polyamides. The mechanism of acceleration is the donation of a hydrogen to the oxygen on the epoxy ring, causing ring opening. Accelerators with a high level of acidity increase the rate of reaction. However, extremely acidic accelerators can extend pot-life by the protonation of the basic amine curing agent, forming an amine salt. Examples of acidic accelerators are nonyl phenol, resorcinol, triphenyl

**Table 2.6** Ultraviolet stabilisers for epoxy systems, with the chemical abstracts service (CAS) registry number

Compound	CAS registry number
2,4-dihydroxybenzophenone	(131-56-6)
2,2-dihydroxy-4,4'-dimethoxy benzophenone	(131-54-4)
2-(2'-hydroxy-5-methylphenyl) benzotriazole	(2440-22-4)
2-[2'-hydroxy-3',5'-(diamyl)phenyl] benzotriazole	(25973-55-1)
ethyl-2-cyano-3,3-diphenyl acrylate	(5232-99-5)
2-ethylhexyl-2-cyano-3,3-diphenyl acrylate	(6197-30-4)

phosphite, salicyclic acid, lactic acid, toluene and *p*-sulphonic acid (Lee and Nivelle, 1967).

**2.2.6.8.2 Basic accelerators.** Basic accelerators are used with acidic curing agents such as anhydrides, novolac or dicyandiamide. They function by attacking the anhydride ring, causing the ring to open and promote bonding to the epoxy ring. Commonly used basic accelerators are tertiary amines and imadazoles.

**2.2.6.8.3 Retarders.** Special solvents have a retarding effect on the curing reaction. A large number of ketones, especially acetone, increase the pot-life via the formation of ketimines. Strong slow-boiling solvents such as tetrahydrofuran and dimethyl formamide are also effective in slowing the reaction (Dow Chemical Company, undated d).

**2.2.6.9 Ultraviolet stabilisers for epoxies.** The function of ultraviolet (UV) stabilisers is to retard light-induced polymer degradation which is caused by electromagnetic radiation emitted by the sun. Commonly used UV stabilisers for epoxy systems are given in Table 2.6 (Dexter, 1982). Only chemical names along with chemical abstracts services (CAS) registry numbers are mentioned; commercially they are known by trade names.

## 2.3 Polyurethanes

Polyurethanes were discovered in 1937 by Otto Baryer and his co-workers at the laboratory of I.G. Farbenindustrie in Leverkusen (Ulrich, 1982). Since their discovery polyurethanes have attained substantial commercial importance. The development of polyurethane technology was delayed by the Second World War. With the shortage of natural rubber during the war their wide versatility enabled them to be developed in a number of application areas. It became clear that urethanes offered greater latitude, and many new products were created.

The urethane linkage is a relatively stable bond. Owing to the availability of many types of urethane compound it is possible to create hundreds of potentially interesting products which are characterised by toughness, chemical and corrosion resistance, abrasion resistance and durability. This combination of properties is hard to match in a single resin, with the exception of epoxies.

Despite some business depressions, the world polyurethane market has shown remarkable growth through the 1980s and 1990s reaching about 6.6 million tons of isocyanates and polyols in 1995.

The consumption of polyurethanes in the construction sector in 1995 was 15% of the total market (Sommerfeld, 1996).

Polyurethanes are obtained by the reaction of polyisocyanates with polyhydroxy compounds, such as polyethers, polyesters, castor oil and glycols. Compounds containing groups such as amino and carboxyl groups may also be used. Thus a typical polyurethane may contain, in addition to urethane groups, aliphatic and aromatic hydrocarbon residues and ester, ether, amide and urea groups.

### *2.3.1 Raw materials for manufacturing polyurethane polymers*

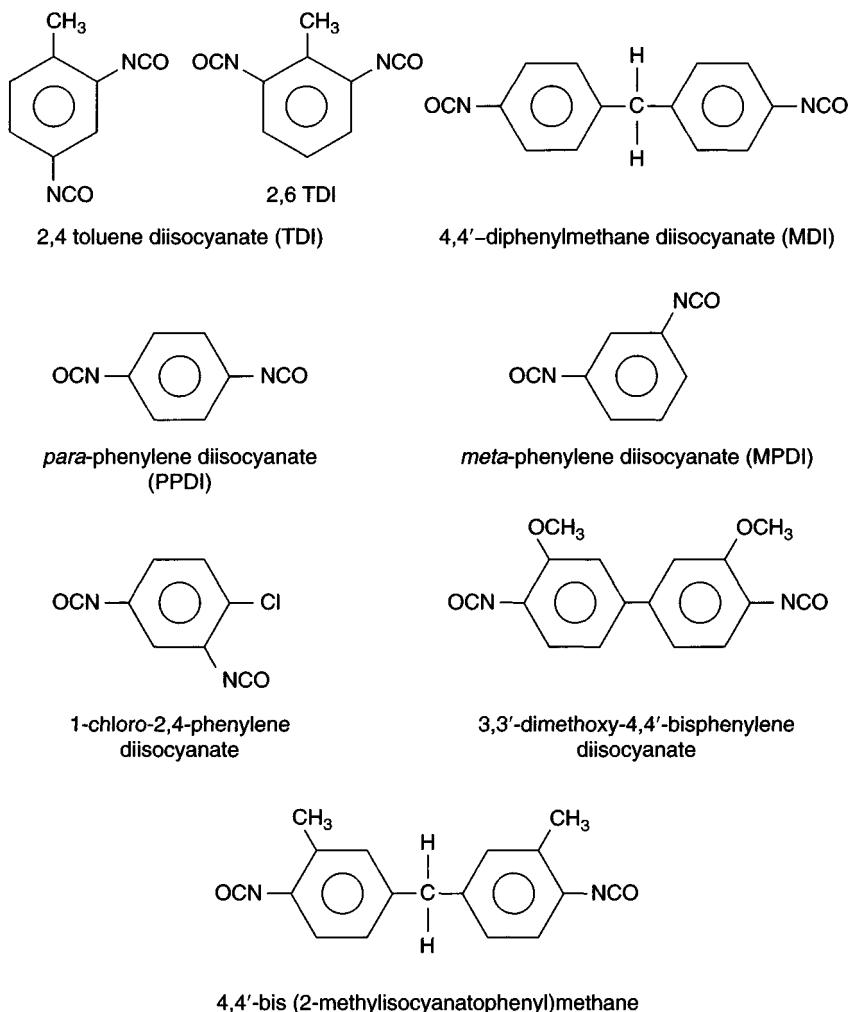
**2.3.1.1 Isocyanates.** The most widely used isocyanates are the 2,4 and 2,6 isomers of toluene diisocyanate (TDI). The manufacture of TDI involves the dinitration of toluene followed by catalytic hydrogenation to a diamine and phosgenation. Separation of the undesired 2,3 isomer is necessary because its presence interferes with polymerisation (Sommerfeld, 1996). TDI is a colourless liquid with a boiling point of 120°C at 100 mm Hg.

4,4'-Diphenylmethane diisocyanate (MDI) is another important raw material in polyurethane manufacture. It is a solid, melting at 37°C, and has a tendency to dimerise at room temperature. Several other aromatic isocyanates are used in the preparation of polyurethanes but are not widely used. Various aromatic isocyanates are illustrated in Figure 2.14.

Polyurethane polymers based on aromatic isocyanates tend to yellow on prolonged exposure to sunlight. Beachell and Ngoc Son (1963, 1964) showed that colour formation could be the result of oxidation of pre-existing amino end-groups, and further oxidation of amines liberated during thermal degradation at 150°C–215°C to form coloured products such as polypseudourea ether and a still unknown material derived from TDI (Figure 2.15).

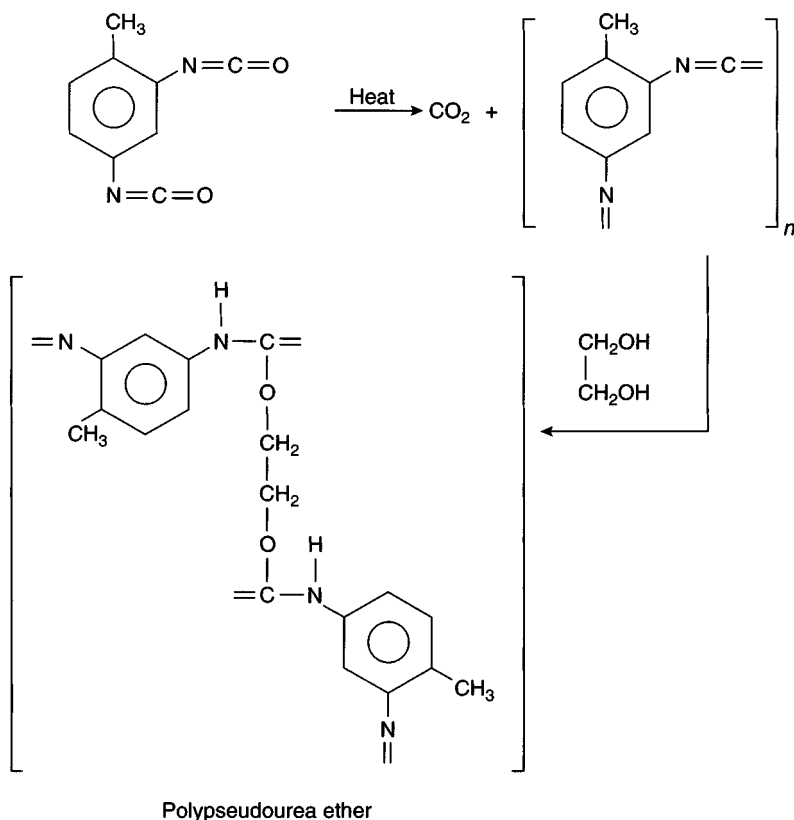
Several other researchers have studied the effect of yellowing in aromatic isocyanate-based polyurethanes, and the effect of yellowing in aromatic isocyanate-based polyurethanes has also been studied. In general, products based on aromatic isocyanates are suitable only for indoor applications.





**Figure 2.14** Some aromatic isocyanates

The first commercial aliphatic diisocyanate to be available is 1,6-hexamethylene diisocyanate (HDI). It is a colourless liquid with a boiling point of  $127^\circ\text{C}$  at 10 mm Hg. It is less reactive than either TDI or MDI, but in the presence of a catalyst the rate of reaction is enhanced. The use of HDI leads to urethane polymers with better resistance to discolouration, hydrolysis and heat degradation than has TDI (Frisch, 1969). A number of aliphatic diisocyanates have become available commercially. These aliphatic diisocyanates have been reported to give excellent colour stability. Some important aliphatic diisocyanates are illustrated in Figure 2.16.

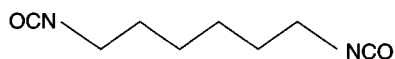


**Figure 2.15** The production of the coloured product polypseudourea ether

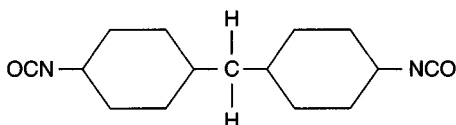
**2.3.1.2 Polyols.** Polyols are multifunctional hydroxy-bearing compounds. They fall into several categories based on chemical type. Polyols are commercially available in a wide range of molecular weights and functionalities. Reactive hydroxyl materials in common use are polyethers, polyesters, polycaprolactones, polybutoximes, polycarbonates, acrylics, alkyds, castor oil, glucosides, sucrose derivatives and so on. Innumerable possibilities exist by combining such polyols with a few commercial isocyanates in various ways.

### 2.3.2 Reactions of isocyanates

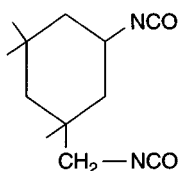
The most common reactions are those between isocyanate and alcohol group [Figure 2.17(a)] or amine group [Figure 2.17(b)]. Carboxylic acids also react readily with isocyanates through the hydroxyl group [Figure 2.17(c)] but are somewhat less reactive than are the primary alcohols and



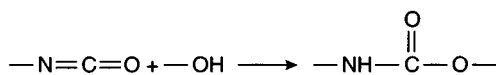
1,6-hexamethylene diisocyanate (HDI)



4,4'-dicyclohexylmethane diisocyanate

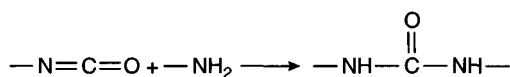


Isophorone diisocyanate (IPDI)

**Figure 2.16** Some important aliphatic diisocyanates

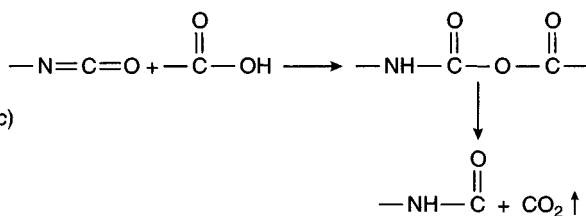
(a)

Urethane



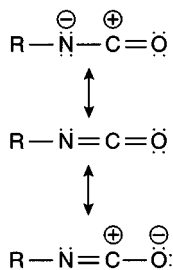
(b)

Urea



(c)

**Figure 2.17** Reactions of isocyanates with (a) the alcohol group; (b) the amine group; (c) carboxylic acids

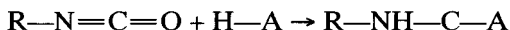


**Figure 2.18** The resonance structures of isocyanates

water. The reaction is catalysed by tertiary amines and many other bases as well as numerous metal compounds. The initial addition product is not stable [Figure 2.17(c)].

In general, isocyanates will react with almost any compound possessing an active hydrogen (i.e. one that may be replaced by sodium) and with a few compounds having hydrogen atoms not readily replaced by sodium (Pigott, 1969).

Isocyanates have three possible resonance states, as shown in Figure 2.18. The reaction occurs by addition to the carbon–nitrogen double bond. In case of compounds with active hydrogen, the hydrogen atom becomes attached to the nitrogen of the isocyanate and the remainder of the active hydrogen compound becomes attached to the carbonyl carbon:

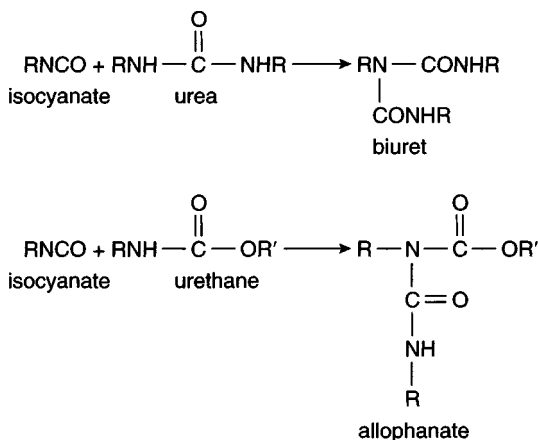


In the majority of cases the addition product is stable, but in some special cases it is only moderately stable and may either dissociate to form the initial reactants again or decompose to other products. Secondary reactions of isocyanates that are important in the formation of urethane polymers are those with urea and urethanes. These reactions result in the formation of biuret and allophanate, respectively (Figure 2.19). The relative reaction rates of active-hydrogen-bearing compounds with isocyanate are given in Table 2.7.

### 2.3.3 Catalysts


The uncatalysed reaction of diisocyanates with polyols does not have any significance in the formation of polyurethanes. Reactions are catalysed by acids and organic bases. Among the good catalysts are tertiary amines and organometallic compounds, mainly tin derivatives.

Catalysts not only affect the rates of the chemical reactions responsible for chain propagation, extension and cross-linking but also affect the ultimate properties of the resulting polymer. Another important function of



**Figure 2.19** The reaction of isocyanate with urea and urethane

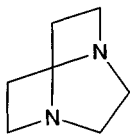
**Table 2.7** The relative reaction rates of active-hydrogen-bearing compounds with isocyanate

Aliphatic amine	 Increasing rate
Aromatic amine	
Primary hydroxyl	
Secondary hydroxyl	
Water	
Tertiary hydroxyl	
Phenol	
Carboxylic acid	
Urea	
Urethane	

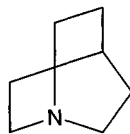
the catalyst is to bring about completion of the reactions, resulting in an adequate 'cure' of the polymer (Frisch, 1969).

Tertiary amines are catalysts for both isocyanate-hydroxyl and isocyanate-water reactions. Generally, an increase in base strength in tertiary amines increases the catalytic strength. However, in the case of triethylene diamine (DABCO) the nucleophilicity is enhanced by the steric configuration. Electron-donating substituents enhance catalytic activity. Some tertiary amines are illustrated in Figure 2.20.

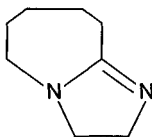
Organotin compounds are effective catalysts for the isocyanate-hydroxyl reaction. Tin catalysts have a slight odour, and low amounts are required to achieve a high reaction rate. Examples of organotin catalysts are stannous octoate, stannous oleate, dibutyltin dilaurate and dibutyltin di-2-ethylhexoate. They are often used in conjunction with small concentrations of antioxidants such as tertiary-butyl catechol resorcinol and tartaric acid.



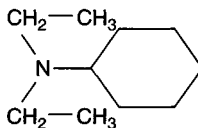
1,4-diazobicyclo (2,2,2) octane



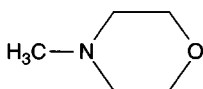
1-azobicyclo (2,2,2) octane



1,8-diazobicyclo (5-3,0) undec-7-ene



N,N-diethylcyclohexylamine



N-methylmorpholine

**Figure 2.20** Tertiary amine catalysts

Catalysts mentioned in this section are also utilised singly or at times in combination for the preparation of foams, sealants, coatings, adhesives and certain types of elastomers.

### 2.3.4 Factors affecting the formation of polyurethanes

The polycondensation reactions leading to the formation of polyurethanes are influenced by a number of factors (Wells, 1969), prominent among which are the:

- structure and functionality of the isocyanate;
- type and location of the substituent;
- structure of the polyhydroxy compound;
- solvent used;
- dilution of the system;
- presence of impurities such as traces of acid in isocyanate;
- temperature, particularly above 100°C.

### 2.3.5 Thermosetting polyurethanes

This type of polyurethane cures irreversibly by chemical reaction at room temperature. Branched or cross-linked thermoset polymers are made with higher functional monomers. Thermoset polyurethanes have a higher

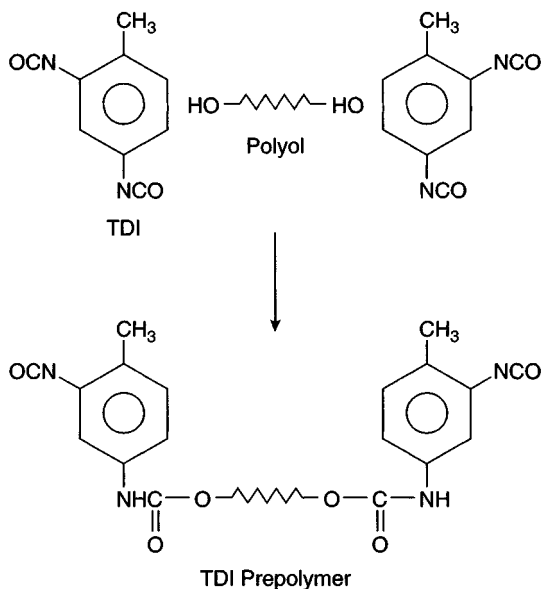
thermal stability but lower impact strength than other polyurethanes. The higher functionality is obtained with higher functional isocyanates, so-called polymeric isocyanates, or with higher functional polyols.

### 2.3.6 Prepolymers

Prepolymers are formed by the reaction between monomeric diisocyanates and a polyol compound. The polyol component can be a single polyol or a mixture of polyols, so that a range of functionalities and molecular weights in the prepolymers is possible. Prepolymers vary from intermediate to high molecular weight 100% solid resin to low molecular weight highly functional resins in solution. Figure 2.21 presents the general reaction of TDI with a polyol. In this case the resultant prepolymer contains no free monomeric TDI.

Prepolymers are characterised by:

- isocyanate type (aromatic or aliphatic);
- polyol type;
- NCO group content;
- solid content;
- functionality;
- molecular weight;



**Figure 2.21** The general reaction of toluene diisocyanate (TDI) with polyols

- flash point;
- vapour pressure.

Given the above information, it is usually possible to determine likely end-uses for the prepolymer. Commercial suppliers are not anxious to divulge full characterisations. Generally, functionality and particularly molecular weight information are withheld. Conversely, for a known end-use the polyurethane synthetic chemist designs a suitable characterisation and formulation for the urethane prepolymer.

Table 2.8 lists the characteristics of commercial prepolymers, taken from the product data sheets of various manufacturers. It is evident that in any of the products, molecular weight information is not provided.

The prepolymerisation reactions of urethanes vary greatly in reaction rate; for example, when MDI is reacted with primary alcohols the rate of reaction is moderate, and the reaction of IPDI with secondary alcohol is slow.

In most cases, the rate of polymerisation is slow under ambient conditions. In order to increase the reaction rate, it is carried out at an elevated temperature, typically in the range of 60°C–90°C, the actual conditions being chosen according to the requirements of the particular system; for example typical conditions for the preparation of an MDI polyether would be 3 h at 70°C–80°C.

Aliphatic prepolymerisation usually requires catalysts in addition to an elevated temperature. Typical conditions are 4 h at 80°C–90°C with 20 ppm stannous octoate. One drawback of using catalysts in prepolymerisation is the promotion of unwanted side reactions and the reduction of shelf-life and stability, particularly with MDI polymers.

Now that we have a background of prepolymers, let us deal with two specific examples which are used in the construction industry: IPDI-based prepolymer and MDI-based prepolymer.

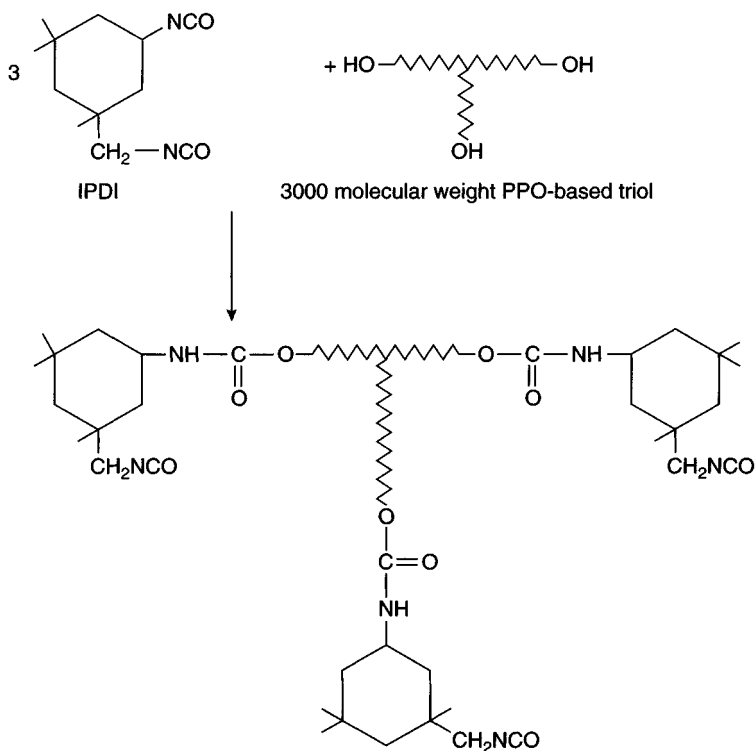
**2.3.6.1 IPDI-based prepolymer.** This is an aliphatic prepolymer formed by the reaction of IPDI with polyether polyol (3000 molecular weight PPO-based triol) (PPO = polypropylene oxide). The NCO group content of such systems is about 3.4%, and the viscosity about 15 000 CP at 20°C. Solid content is typically 98%–100%. The general reaction is given in Figure 2.22. This prepolymer may typically be used in two-part elastomer systems.

**2.3.6.2 TDI-based prepolymer.** This aromatic type of prepolymer is formed by the reaction of TDI with short-chain polyols. The resultant prepolymer will have an NCO group content of 14.2%, a viscosity of 1000 CP at 20°C and a solid content of 75%. This prepolymer may typically be used as a primer or as a base for one or two pack polyurethane coatings. The reaction is represented in Figure 2.23.



**Table 2.8** Characteristics of commercial polyurethane prepolymers. Molecular weight information is withheld by the manufacturers

	Prepolymer			
	1	2	3	4
Appearance	Straw-Coloured Liquid	Straw-Coloured Liquid	Straw-Coloured Liquid	Straw-Coloured Liquid
Approximate functionality	2.7	3.5	2	2.7
Maximum viscosity at 25°C (cP)	10 000	12 500	10 000	20 000
Density at 20°C (g/cm <sup>3</sup> )	1.045–1.055	1.033–1.045	1.140–1.050	1.055–1.065
NCO group content (%)	2.4–2.7	3.9–4.2	3.2–3.6	3.2–3.6
Maximum free monomer (percentage TDI)	2	2	2	2
Minimum solids content (%)	98	98	98	98
Flash point (Abel closed cup) (°C)	> 100	> 100	> 100	> 100
Boiling point (°C)	> 200	> 200	> 200	> 200
Vapour pressure (mm Hg)	< 0.5	< 0.5	< 0.5	< 0.5
Vapour density (air = 1)	> 1	> 1	> 1	> 1
Evaporation rate (BUAC = 1)	< 0.1	< 0.1	< 0.1	< 0.1



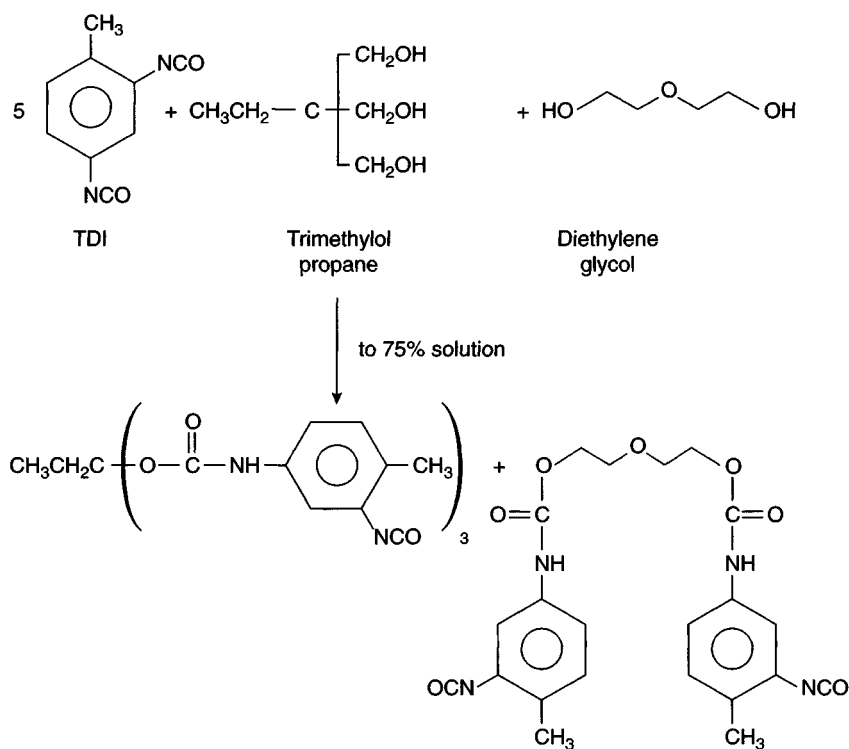
**Figure 2.22** Synthetic route for prepolymers based on isophorone diisocyanate (IPDI).  
PPO = polypropylene oxide

**2.3.6.3 Summary.** Prepolymers have played an important part in practically every branch of urethane polymer technology. They offer several functions (Wells, 1969); mainly they

- provide a source of reactive groups which, by dilution, may be more easily controlled in subsequent polymer building, giving products that are more uniform from batch to batch;
- provide a means of avoiding the use of elaborate metering equipment sometimes necessary for one-shot techniques (e.g. in commercial foam operations);
- provide a means of handling safely monomers having noticeable vapour pressure.

### 2.3.7 Additives for polyurethane-based products

The function of additives is to control the properties of end-product and to reduce the cost.



**Figure 2.23** Synthetic route for prepolymers based on toluene diisocyanate (TDI)

**2.3.7.1 Surfactants.** Silicone surfactants lower the surface tension and emulsify incompatible ingredients. Copolymers of polydimethylsiloxane and polyoxyalkylene were the originally used surfactants. Surfactants with Si—O—C bonds are hydrolysable, but those with only a Si—C bond are non-hydrolysable. Several non-hydrolysable alkyl pendant silicone copolymers are used as surfactants for specific formulations (Seymour, 1992).

**2.3.7.2 Fillers.** Fillers mentioned for epoxy systems (subsection 2.2.6.4) are used in polyurethanes too. Ground calcium carbonate (coated as well as uncoated) is commonly used. Barium sulphate, silica fumes, wood flour and milled glass fibres are also used.

**2.3.7.3 Pigments.** Addition of light-fast pigments reduces the rate of degradation in the case of aromatic polyurethanes. Organic dyes supply colour but do not scatter light and hence are not effective as light stabilisers. The principal pigments used are carbon black and titanium dioxide. Coloured pigments based on iron oxide are often employed. Lead

pigments are also suitable but are now being avoided in light of environmental issues.

**2.3.7.4 Ultraviolet stabilisers.** Stabilisers based on hindered amines are effective.

**2.3.7.5 Flow-control agents.** Secondary butyrates serve as good flow-control agents.

**2.3.7.6 Antioxidants.** Hindered phenol antioxidants such as 2,6-ditertiary butyl-4-methylphenol (BHT) controls the exotherm in the reaction between diol and diisocyanate. When acidic flame retardants are present in the formulation, amine antioxidants are preferred (Seymour, 1992).

**2.3.7.7 Antimicrobials.** 2-Bromo 2-nitropropane-1,3-diol and 2,4-dichlorobenzyl alcohol are effective biocides in polyurethane formulations.

**2.3.7.8 Solvents.** Some polyurethane coatings are solvented. Polyurethane prepolymer solutions are also supplied as solutions in organic solvents. Polyurethane-grade solvents by definition must have a low content of active hydrogens; therefore, alcohols and amines, etc. are not suitable, nor are other solvents containing more than 0.5% water.

Commonly used solvents are:

- 2-ethoxyethyl acetate and propyl versions (i.e. cellosolve acetate, oxitol acetate, etc.);
- methylethyl ketone (and other ketones);
- ethyl acetate;
- halogenated hydrocarbons;
- xylene (and other aromatic hydrocarbons).

## 2.3.8 Water-borne polyurethanes (polyurethane dispersions)

Some 15 years ago, water-borne polyurethanes, or polyurethane dispersions (PUDs), started gaining in importance. Environmental and legislative pressures have driven industry to concentrate on water-borne polymers. PUDs have experienced an upsurge in importance over the past few years in particular. A major reason for this upsurge has been a number of noteworthy applications. The important ones for the construction industry are applications concerning anticorrosion coatings, wood paints, coatings for mineral substrates, etc.

Aqueous PUDs fall into two major classes:

1. aqueous polymer dispersions prepared by emulsion polymerisation;
2. dispersions of preformed polymers in water.

Synthetic processes for high molecular weight PUDs include the acetone process, the melt dispersion process, the prepolymerising process and the ketimine process (Arnoulds, 1990). The first step common to all these processes is the conventional synthesis of polyurethane in which diol or polyols are reacted with diisocyanates. The second step involves dispersion in water (Satguru *et al.*, 1994). In order to achieve low viscosity in the system, one of the following methods is used (Satguru *et al.*, 1994):

- if the urethane polymer is of low molecular weight, a chain-extension step is required at the aqueous dispersion stage in order to achieve the necessary high molecular weight (e.g. the ketimine process or the prepolymer mixing process);
- the urethane polymer may be dissolved in solvent and the solvent removed after the aqueous dispersion step (the acetone process);
- the urethane polymer may be heated to facilitate dispersion in water (the melt dispersion process).

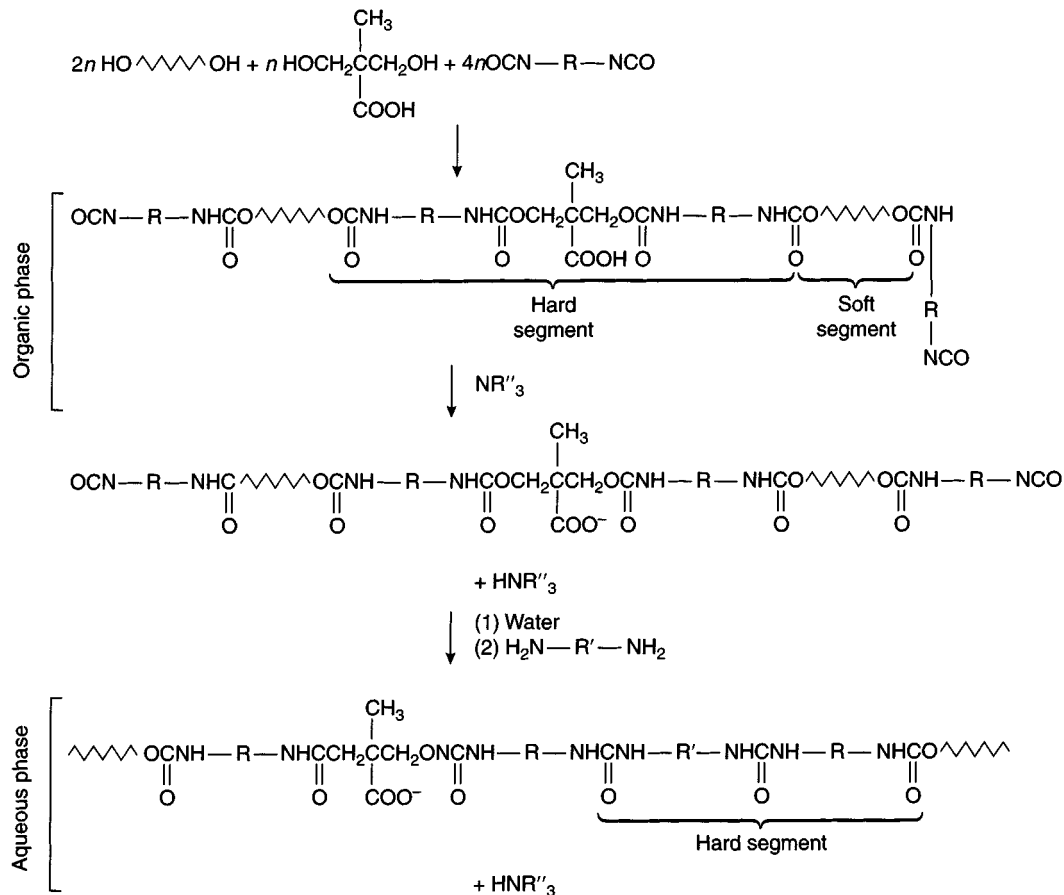
The hydrophilic centres in PUDs are basically of three types (Klein and Schwab, 1993):

- non-ionic groups (e.g. polyethylene oxide chains);
- cationic groups (e.g. alkylated or protonated tertiary amines);
- anionic groups (e.g. carboxylate or sulphonate groups).

The above groups function as internal emulsifiers, and introduction of these hydrophilic groups makes it possible to produce stable aqueous emulsions. Most of the polyurethane dispersions used are anionic.

A synthetic scheme is presented in Figure 2.24 as reported by Klein and Schawb of Hoechst (1993). In this reaction an aqueous, anionically stabilised polyurethane dispersion is prepared by reacting an excess of diisocyanate with a long-chain, usually linear, polyol, a bis-hydroxycarboxylic acid and another low molecular weight glycol to form an NCO-terminated prepolymer with a segmented structure. In the polymer the long-chain polyol units form soft segments, and the urethane units built up from diisocyanate, glycol and bis-hydroxycarboxylic acid form hard segments. Neutralisation of the carboxyl groups with amines yields the anionic hydrophilic centres, which are essential for the dispersion process and subsequent stabilisation of the resins in the aqueous phase.

Film formation of PUDs involves coalescence of the particles and the formation of a continuous film. A PUD particle has a hydrophilic shell and a hydrophobic core. Upon film formation, there is a very slow process of coalescence on a molecular level whereby there is a physical barrier to polymer chain mixing. The resultant coatings have hydrophilic and hydrophobic regions, which create a more water-permeable film (Chainey *et al.*, 1985).



**Figure 2.24** Scheme for an aqueous, anionically stabilised polyurethane dispersion. Source: Klein H.P. and Schwab, M., Aqueous polyurethane dispersions – an environment friendly alternative for high quality paint systems, *Resin News*, number 29 (July); published by Hoechst AG, Frankfurt, 1993

Tramontano and Blank (1995) reported the preparation of a low molecular weight, hydroxyl/carboxyl functional water-borne polyurethane dispersion via monoisocyanate chemistry which is readily cross-linkable with melamine-formaldehyde resin. Such cross-linking can improve the water resistance because of the reaction of some of the hydrophilic groups (Tramontano and Blank, 1995).

Xiao *et al.* (1995) developed a one-pack cross-linkable water-borne coating from anionic-blocked isocyanate-containing urethane prepolymer. The anionic-blocked urethane dispersions were prepared from poly(oxypropylene) glycol, polyarylpolyisocyanate, dimethylolpropionic acid and methylethyl ketoxime. The coatings based on these dispersions were reported to show good mechanical properties and chemical resistance.

Bittner and Epple (1996) reported the development of aqueous and high-solid two-pack polyurethane paint which is useful as industrial finishing.

In today's market, a variety of PUDs is available. Coatings formulated with PUDs offer excellent properties, such as: adhesion to various substrates, resistance to chemicals, solvents and water; abrasion resistance; flexibility; toughness. Water-borne polyurethane coating systems are probably one of the fastest growing areas in the coating industry at present. Most of the solvent-borne polyurethane polyol coatings are relatively high in solvent content and do not qualify in low volatile organic compound (VOC) applications. For this reason there is an increased interest in water-borne polyurethane coatings. However, many water-borne polyurethane coating systems cannot meet some of the performance requirements, unlike the corresponding solvent-based coatings. This is presumably because of a lack of coating systems which have appropriate cross-linking. Research is underway in this field and very soon we may expect to have an excellent water-based PUD which may provide the coating with all the properties obtainable with a solvent-based coating.

## 2.4 Acrylics

Acrylics are defined as the family of materials having a similar chemical structure but a wide range of properties. They result from the polymerisation of esters and other derivatives of acrylic acid and methacrylic acid.

Acrylic esters and methacrylic esters have been known for over a century, but the serious study of their polymers dates back to the pioneering efforts of Rohm, beginning with his doctoral thesis in 1901 (cited in Lushin and Myres, 1982). The first commercial production of an acrylic polymer occurred in 1927.

The major contribution to the research and development of acrylics was made by Rohm and Haas Co., one of the major manufacturers of all types

## **3 Epoxies in the construction industry**

### **3.1 Introduction**

Epoxy systems are widely used in building and civil engineering applications and occupy a dominant position compared with other polymers. The major characteristics of epoxy resin systems provide an excellent combination of properties, including:

- excellent abrasion resistance;
- very low shrinkage during and after cure;
- high mechanical strength;
- excellent adhesion to most building materials;
- wide range of cure schedules to suit different climatic conditions;
- use performance can be achieved within hours.

Since the early 1950s when epoxy adhesives became commercially available, continuous innovations have been made, resulting in a diverse range of applications. In 1953 the Shell Chemical Corporation initiated field tests to evaluate epoxy systems as surfacing materials on highways, following successful laboratory tests by the company. The technique of epoxy injections for repair was first used in the late 1950s. The use of epoxy as a grout to bond bolts or doves to hardened concrete was also attempted in the late 1950s.

Epoxy seal coating was first applied as test patches in industrial plants in 1953. In 1957 epoxy polymer concrete was first used as a wearing course in the repair of popouts and spalled areas on the surfaces of various bridge decks in California (ACI, 1993).

In today's world, epoxy technologies have become firmly established in the construction sector, offering countless applications in all of the industrialised countries and in the Third World too. Products based on epoxies are used for an amazing variety of applications: hard-wearing coatings and flooring resistant to water, chemicals and abrasion, thin-layer non-skid surfacing for roads and bridges; interlayer sealing membranes for bridges; mortars for repairs and load-bearing supports; grouts for the anchoring of crane rails and machines; adhesives for the structural bonding of prefabricated concrete elements; anchoring of reinforcing steel, rock bolts, pre-stressing anchors, etc.; injection repair of cracks; repair structures in general. All of these technologies will be covered in this chapter.



By combining epoxies of different molecular weight, type and reactivity with a variety of different curing agents one has the possibility to formulate two-component systems for nearly any application in civil engineering or the building industry. Table 3.1 outlines the properties, products and application areas of epoxy systems.

## **3.2 Properties of cured epoxies**

### *3.2.1 Abrasion resistance*

Epoxies have an excellent resistance to abrasion. The abrasion resistance of a particular system depends upon the type of formulation and conditions. For example coatings have the capacity to resist abrasion from rubber wheels, whereas screed floorings, repair mortar and self-levelling floors can resist thousands of cycles from steel wheels.

Fillers play a key role in improving abrasion resistance. Those fillers which increase the surface hardness (e.g. silica sand) offer high abrasion resistance to the system.

### *3.2.2 Adhesion*

Epoxies adhere very well to almost all materials used in construction; for example concrete (wet or dry) masonry, metals, glass, ceramics, etc. Good surface preparation is essential to improve the adhesion performance. Priming the surface of the substrate also ensures good adhesion. Depending upon variations in type of concrete, it is advisable to carry out an adhesion test. These tests are performed in accordance with the ASTM D-4541 method which is generally referred as the 'pull off test'. A number of mechanisms have been proposed (Lee and Nivelles, 1967) to explain the adhesive characters of epoxies. However, this property can to a certain extent be attributed to their low curing shrinkage, prolonged dimensional stability, high tensile and compressive strengths and resistance to moisture and many chemicals (ACI, 1993).

### *3.2.3 Chemical resistance*

The chemical resistance of epoxies is dependent on the type of curing agent used and can be tailored to meet the specific end-use. In terms of molecular structure, systems with more thermal stability have a higher order of chemical resistance.

Properly cured epoxy formulations are resistant to most caustics, solvents and many acids except the strongest oxidising acids. Chemical resistance data from the product manufacturer are helpful in selecting the

**Table 3.1** Properties, products and application areas of epoxy systems

Product and properties	Application area
Structural adhesive: Excellent adhesion to concrete and steel Ability to cure under moist conditions Variable application time to suit different climates	Bonding hardened concrete and fresh concrete
General purpose adhesive: Adhesion to wood, stone, bricks, metals, plastics, ceramics	Various bonding applications
Tile adhesives: High bond strength Chemical resistance	Bonding ceramic tiles to concrete or steel
Crack injecting systems: Excellent adhesion to concrete in dry or damp conditions Ability to cure at low temperatures near freezing point Mechanical strength	Static cracks in concrete structures
Resistant coatings: High build; solventless Range of colours Corrosion resistance Chemical resistance Excellent adhesion	Potable water tanks Food industry Internal pipelining, etc.
Laminate coatings: Chemical resistance Abrasion resistance Adhesion	Storage tanks in refineries and oil fields Water purification units Paper industry
Epoxy-tar coatings: Chemical resistance Bacterial resistance Corrosion resistance Reasonable weathering resistance	Effluent plants Sewage works Chemical processing plants
Floorings: Excellent bonding to concrete High strength High impact resistance Chemical and abrasion resistance	Floor toppings on concrete in numerous applications
Grouts: Range of viscosities High strength Resistance to impact loading	Support beneath rails, machine bases and industrial equipment
Anchors: Adhesion to wet and dry substrates High mechanical strength Resistance to alkaline hydrolysis Short curing time	Anchoring Mining and tunnelling Civil engineering
Antiskid systems (road resurfacing epoxies): Skid resistance Resistance to water, de-icing salts, fuels, dilute acids and alkalis	For deslicking a smooth roadway

material for a particular application. Table 3.2 gives chemical resistance data for epoxy resins with various hardeners.

### 3.2.4 *Mechanical strength*

These properties include compressive strength, flexural strength and tensile strength. They are tested according to British standard BS 6319. Compressive strength is the measure of resistance of a material to a crushing force; flexural strength is the resistance of a material to bending stresses; tensile strength is a measure of the pull required to break a sample of material.

### 3.2.5 *Resilience*

Epoxyes can return to their original shape, after deformation, provided their elastic limit has not been exceeded.

### 3.2.6 *Heat distortion temperature*

The heat distortion temperature (HDT) of a diglycidyl ether of bisphenol A (DGEBA) with a common curing agent is 90°C–190°C, but with highly functional resins and curing agents values as high as 300°C have been measured (Lee and Nivelle, 1967).

### 3.2.7 *Electrical properties*

Epoxyes are excellent electrical insulators. Electrical properties are reduced on increasing the polarity of the molecules. Addition of metallic fillers, metallic wools and carbon black convert the non-conductive epoxy formulation into an electrically conductive system. Non-conductive fillers increase the arc resistance and to some extent increase the dielectric constant.

### 3.2.8 *Thermal shock resistance*

Epoxy systems with flexibilisers and properly-selected fillers exhibit high resistance to rapid changes in temperature and do not show signs of cracking or shattering. Rigid epoxy systems can cause severe problems. Better formulated systems can withstand repeated thermal shock cycles from 180°C to –75°C without failure.

### 3.2.9 *Thermal stability*

It is the ability of epoxyes to withstand high temperatures and at the same time maintain specified properties. With high-temperature ageing, epoxy

**Table 3.2** Chemical resistance of epoxy systems D.E.R. is the registered trademark of Dow Epoxy Resins. Data reproduced courtesy of Dow Chemical Company, Midland, MI, USA

	Aliphatic amine XU 19036.00 <sup>a</sup>				Cycloaliphatic amine/aliphatic amine <sup>b</sup> Ancamine 2280/D.E.H. 24 blend (80/20)		
	D.E.R. 354 LV	D.E.R. 383	D.E.R. 331	D.E.R. 364	D.E.R. 354	D.E.R. 331	D.E.R. 331/C12-C14 glycidyl ether (94/6) blend
Acetone	9.20/13.14	19.5/24.9	21.18/D ( $< 28$ days)	21.6/D ( $< 7$ days)	D ( $< 3$ days)	D ( $< 2$ days)	D ( $< 2$ days)
10% Acetic Acid	26.97/D (7 days)	D ( $< 3$ days)	36.48/D ( $< 7$ days)	19.6/49.9	Not Tested	Not Tested	Not Tested
Distilled Water	0.27/1.04	0.26/1.09	Not Tested	Not Tested	0.32/0.98	0.28/1.06	0.30/1.10
Xylene	0.06/0.06	0.62/0.83	0.51/0.93	2.66/7.7	Not Tested	Not Tested	Not Tested
Methanol	2.0/3.89	3.07/5.21	3.47/6.09	5.65/12.74	Not Tested	Not Tested	Not Tested
Concentrated Sulfuric Acid	Not Tested	Not Tested	Not Tested	Not Tested	0.78/0.94 <sup>c</sup>	D ( $< 1$ day)	D ( $< 1$ day)
10% NaOH	Not Tested	Not Tested	0.19/0.83	0.16/0.66	0.22/0.83	0.19/0.84	0.22/0.83
10% Nitric Acid	Not Tested	Not Tested	Not Tested	Not Tested	0.54/1.65	0.55/1.65	0.55/1.68
10% Sulfuric Acid	Not Tested	Not Tested	Not Tested	Not Tested	0.58/1.87	0.51/1.78	0.54/1.79

<sup>a</sup> Clear casting coupons (3"  $\times$  1"  $\times$  0.125") cured with an aliphatic amine XU 19036.00 for 14 days at 25°C and 50% relative humidity. Coupons were immersed in the chemical and tested for percentage weight gain; the above values are for 3 day and 28 day exposures.

<sup>b</sup> Clear casting coupons (3"  $\times$  1"  $\times$  0.125") cured with Ancamine 2280/D.E.H. 24 Blend (80/20) for 14 days at 25°C and 50% relative humidity. Chemicals were immersed in the chemical and tested for percentage weight gain; the above values are for 3 day and 28 day exposures.

<sup>c</sup> These coupons experienced weight gain then weight loss (maximum gain 1.29% at 14 days).

Note: D = destroyed; the first figure given under each heading is for 3 days, and the second entry is for 28 days.

systems generally exhibit loss of strength, reduction in properties and embrittlement owing to loss of volatile fragments. Further increments in temperature result in charring followed by cracking and decomposition.

### *3.2.10 Exothermic nature*

Epoxies develop heat during their cure, resulting in a substantial increase in temperature in the reactive mixture. This temperature increase is known as an exotherm and is measured by a thermocouple.

Modified curing agents with a low exotherm are available, which appreciably reduces the exotherm. Further, use of a high surface area to volume ratio during mixing and application will keep the temperature rise to a minimum.

### *3.2.11 Shrinkage*

Shrinkage is the reduction in volume during cure. Epoxies have a low curing shrinkage. Shrinkage may be reduced through the use of fillers.

### *3.2.12 Thermal expansion*

Thermal expansion is a function of the resin, curing agent, modifiers, diluents and fillers. A higher expansion rate is found for more highly flexibilised systems, and a lower expansion rate is shown for highly filled formulations.

### *3.2.13 Thermosetting properties*

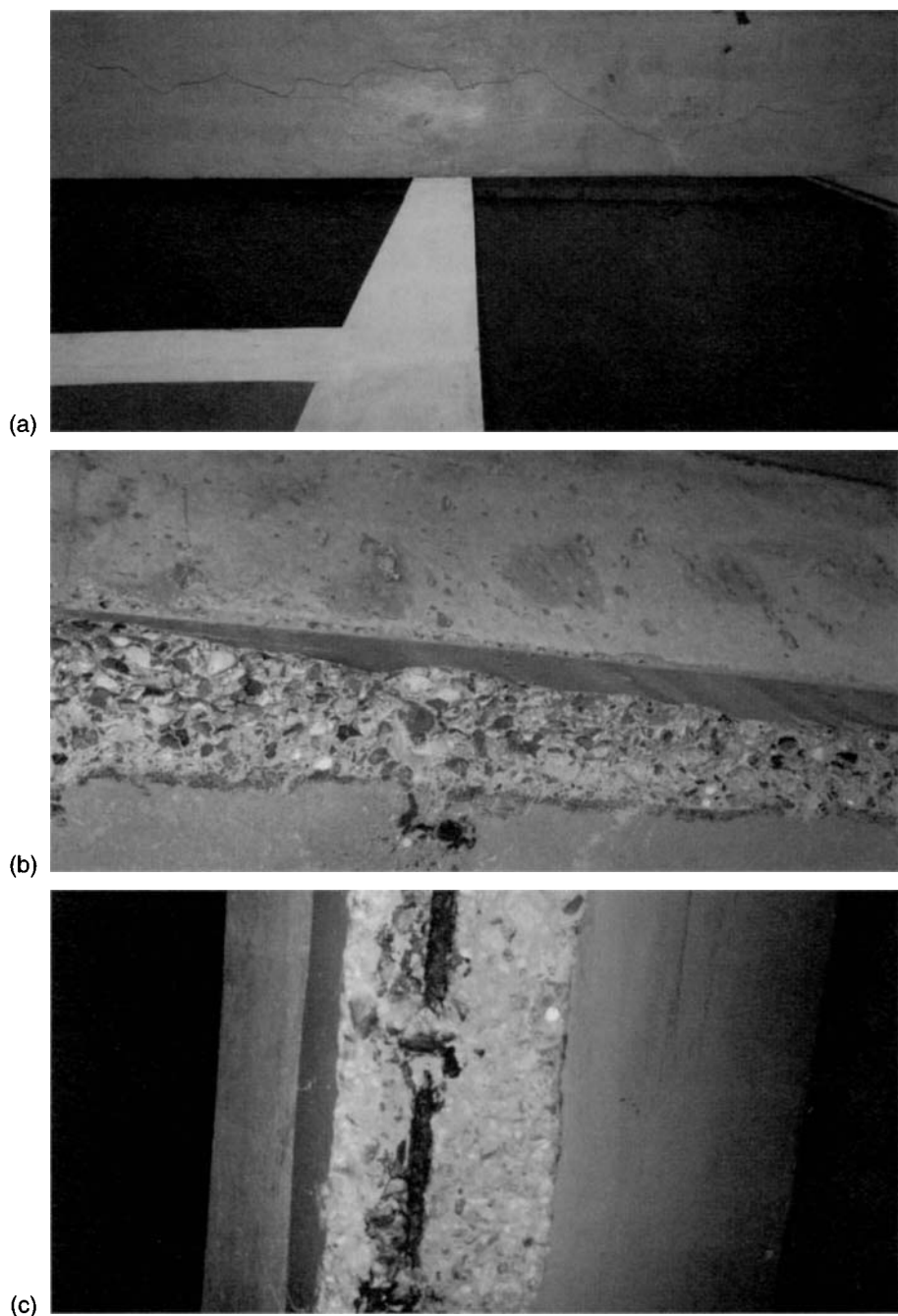
Epoxies undergo an irreversible curing reaction and cannot be reliquefied by heating.

### *3.2.14 Flammability*

Epoxy formulations are flammable in character, ranging from slow burning to self-extinguishing.

## **3.3 Epoxy repair mortars**

Traditionally, durable concrete is vulnerable to the ravages of the modern environment, resulting in the decay of reinforced concrete. Symptoms of such decay are cracking, spalling, rusting of exposed steel reinforcement (Figure 3.1) and staining of concrete surfaces (Fosroc, 1995). All these symptoms seriously weaken the structure. The main reasons are physical



**Figure 3.1** Symptoms of concrete decay: (a) cracking of a concrete beam; (b) spalling of concrete; (c) rusting of steel reinforcement

damage, chloride-induced corrosion, carbonation and frost damage. Cement renders are used in many such repair work, but they are not effective where high strength, fast curing and chemical resistance are required. Under such conditions it becomes essential to use resin-based repair products. Mortars based on epoxy resin effectively and efficiently perform such assignments and are preferable compared with other polymeric mortars. These repair mortars restore the structural integrity of the structure and halt further decline.

Epoxy mortars are 100% solids and are available in different grades. They are mostly three-component products containing an epoxy resin base, curing agents and graded aggregates of silica sand. A few are also available as two-component products, the first component containing thixotropic epoxy resin base and the second a curing agent. Such mortars have fine aggregates and a pasty consistency. All the components are mixed on site. Owing to a short working life it is necessary to plan properly to avoid wastage of material.

Epoxy mortars are suitable for horizontal, vertical and overhead applications. Advantages of these mortars are

1. early development of strength, which makes them suitable for structural use;
2. excellent abrasion and impact resistance;
3. ability to cure under damp conditions;
4. impermeability to water in the cured condition;
5. resistance to many chemicals;
6. high bond strength;
7. solvent-free and thus there is no irritating smell and they are safe;
8. the non-shrink cure.

Most of the commercially available mortars possess approval of the Water Research Council for their suitability for use with potable water in accordance with BS 6319 part 4 and BS 5080 part 1.

Primers are not recommended for dry surfaces by most of the manufacturers. However, for moist substrates, a primer ensures good adhesion. Application is performed by trowels. High-functionality curing agents are required to achieve the necessary compressive strength. Filler-type grading and loading determine the application and final mechanical properties.

Applications of epoxy repair mortars are:

- repair of spalled or honeycombed concrete;
- general repairs, renovations and rendering of soffits, undersides of floors, kerbstones, etc.;
- sewerage works, manhole linings, pipes;
- repair of damaged concrete edges;
- bridge decks;
- concrete runways.

### 3.4 Epoxy adhesives

Epoxy resin adhesives were introduced into the construction industry in the early 1960s. The main advantage of epoxy adhesives in this market is their capacity to join two dissimilar materials and provide outstanding bonds to nearly all materials, with the exception of a few thermoplastics (Lee and Nivelle, 1967). Other properties are high mechanical strength (tensile and compressive), thermal resistance, toughness, low shrinkage, high adhesive strength, inertness, dimensional stability and resistance to a range of chemicals and climatic conditions.

Epoxy resin adhesives are two-component materials and can be tailor made to meet most of the different processing requirements and ultimate performance properties that are required in different applications. This may be done through the correct choice of curing agent or combination of curing agents and by the addition of fillers and auxiliaries. Fillers are added mainly as extenders to resin systems in order to reduce the cost of one or both of the major components. Occasionally, pigmentation is required in order to allow visual identification that the epoxy resin and curing agent components have been mixed homogeneously.

The rate of curing depends primarily on the reactivity of the resin and curing agent. It is also dependent on the quantity of mix and on temperature. The materials used in the construction industry that can be bonded with epoxy resin adhesives are: metals and metal alloys, concrete, natural stone, fibre cement and plaster, ceramic materials, glass, china and porcelain and wood.

Pretreatment of the surface is essential to ensure good bonding. The properties of an adhesive in a particular application are determined by the application conditions and bond strengths. They are dependent on the composition of the adhesive, the properties of the bonded materials and the various environmental conditions, both during and after application.

Depending upon the choice of curing agent, it is possible to formulate epoxy adhesives as flexible or rigid. Polyamide and polysulphide curing agents impart flexibility. Rigid systems contain aliphatic amines such as diethylene triamine (DETA), triethyl amine and catalytic amines (Lee and Nivelle, 1967). A flexible and tough epoxy provides improved adhesion compared with a brittle epoxy because it can yield considerably before fracture and distribute forces through the material matrix to reduce stress concentrations (Munger, 1982).

Temperature has certainly an effect not only on the mechanical strength but also on the bond strength of the adhesive joints. Loss of strength occurs near the heat deflection temperature (HDT) (Lin and Deon, 1996).

Internal stresses may occur within the adhesive joint as a result of the different shrinkage rates of the adhesive and the work pieces, which will reduce the bond strengths. In general the strength of rigid epoxy resin



adhesives changes only fractionally from  $-200^{\circ}\text{C}$  to room temperature (Witco, undated).

At higher temperatures above the glass transition temperature,  $T_g$ , the adhesives become plastic and start to lose their bond strength. Normally, the softening point of unmodified cold-cured resin systems lies between  $40^{\circ}\text{C}$  and  $100^{\circ}\text{C}$ .

ASTM C 881 (1983) provides a classification of epoxy resin bonding systems by type, grade, class and colour. In this standard, there are seven types based on applications, three grades depending on viscosity and consistency requirements and six classes (A–F) according to the range of temperatures for which they are suitable. There is also an option of pigmentation without any restriction to a particular colour.

Depending upon the end-use, an epoxy adhesive can be classified further as a structural adhesive, general purpose adhesive or tile adhesive.

### 3.4.1 *Structural adhesives*

The most important application of epoxies in civil engineering is for bonding concrete to concrete and concrete to other materials. Epoxy resin adhesives possess excellent adhesion properties with concrete and can cure under moist conditions. They are used to ensure a good bond in hardened to hardened concrete and hardened to wet concrete. Hardened concrete is concrete that has been laid for some time. The level of water in the concrete matrix is an important factor and should be less than 5% to avoid future failure as a result of osmotic pressure (Anchor Chemicals/Air Products, undated a). Apart from concrete-to-concrete bonding, these adhesives have proved to be highly suitable for structural adhesion, such as bonding precast concrete components, bonding steel reinforcement to concrete and anchoring steel bars into concrete (Heugenschmidt, 1976).

Structural adhesives are solvent-free compositions and can be formulated to give varying pot-lives, making them suitable for temperate as well as tropical climatic conditions. A long pot-life makes the adhesive suitable for use with form work or where additional steel reinforcement has to be fitted.

Some of the specific applications of epoxy structural adhesives are roads, bridges, pavements, loading bays etc.,

### 3.4.2 *General purpose adhesives*

General purpose epoxy adhesives are well suited for bonding common construction materials such as wood, stone, brick, metals, glass, rubber, plastic, ceramics, etc. They are particularly suitable for the repair of damaged items with closely fitting joint surfaces which require a fine glue



**Figure 3.2** Epoxy tile adhesive: sample representation

line. These adhesives are two-component solvent-free materials with exceptional adhesive properties on curing.

### *3.4.3 Tile adhesives*

These adhesives are used for bonding ceramic tiles to concrete or steel (Figure 3.2). A high filler content ensures a non-slump paste, making them suitable for vertical applications. Epoxy tile adhesives are supplied in three-component packs containing base, hardener and filler. The cured material has a high bond strength to steel, concrete and tiles. Owing to excellent resistance to water, acid and alkalis of the cured adhesive, it is possible to wash the tiles with detergents and other cleaning acids.

Such adhesives are often applied in places where chemical resistance is required, for example, laboratories, food processing plants, hospitals, abattoirs, commercial kitchens, swimming pools, and so on.

## **3.5 Epoxy injections for cracked concrete**

Concrete structures often show cracks. There are several reasons for the formation of these cracks, including physical effects, drying shrinkage, crazing, thermal effects due to seasonal variations in external temperature, early thermal contraction, freeze-thaw cycles and structural effects such as overloading and impact (Concrete Society, 1982).

In general, horizontal slabs develop cracks because of heaving or settling of the soil on which a concrete slab is placed. On vertical placements,

severe stresses and strains will inevitably result in cracking (Maslow, 1982). Typical examples of prime candidates to exhibit cracking are buildings, monuments, bridges, foundation walls, dikes, dams, and so on.

In reinforced elements, cracks of small width (hairline cracks less than 0.1 mm) are generally of little consequence and can be tolerated without affecting the serviceability of the structure (Hewlett and Morgan, 1982). Cracks of widths much greater than 0.5 mm, however, can seriously weaken the structure and increase the deflections under load and in already weakened structures they increase the possibility of reinforcement corrosion, which leads to further downgrading (Hewlett and Morgan, 1982). In order to prevent further deterioration it is most important to repair such cracks.

Crack repair restores structural integrity, seals the cracks against moisture and restores appearance. Epoxy injection systems are employed to fill, fine or coarse cracks in horizontal or vertical surfaces (Figure 3.3); conventional equipment can be used. The benefits of epoxy injection systems are:

- excellent adhesion to dry or damp concrete;
- moisture tolerance;
- dependable curing even at low temperatures (e.g. near freezing point);



**Figure 3.3** A wide, non-moving, crack; such cracks can be repaired with epoxy injection systems

- resilience and outstanding mechanical load distribution which prevents follow-up cracks in the substrate arising from excessive mechanical stresses;
- non-shrinkage;
- resistance to most chemical environments encountered by concrete.

Epoxy crack injection systems are unfilled compositions, based on low-viscosity liquid epoxy resins and low-viscosity moisture-tolerant hardeners. The low viscosity of the system aids penetration into fine cracks and achieves the right balance of gel time (Anchor Chemicals/Air Products, undated a). Cracks as narrow as 0.05 mm can be filled with epoxy injection systems (CCM, 1985).

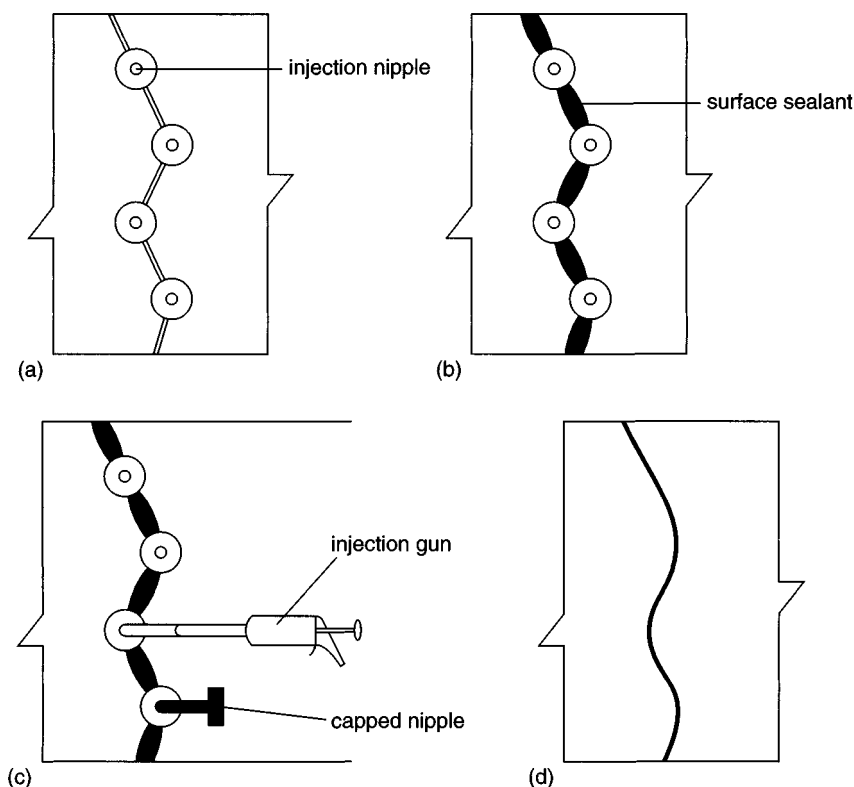
The crack-repair process also utilises a thixotropic epoxy compound known as a surface sealant. This is spread over the face of the crack primarily to prevent liquid epoxy binder from oozing out when injected into the cracks. It is also used for bonding the injection nipples to the surface of the cracks.

Before the epoxy system is injected grease, dirt and dust should be removed completely by proper treatment. The following steps are used for injection into a vertical crack (such procedures may also be followed to repair horizontal cracks).

1. Clean the crack and insert the injection nipples, made of metallic tubing [Figure 3.4(a)].
2. Apply surface sealant on the crack and allow it to cure (it usually cures in one hour) [Figure 3.4(b)].
3. Inject the epoxy resin binder by a double-acting hydraulically-driven piston. Start at the lowest nozzle and work upward. At each stage as each nozzle and hole is filled cap the nipple to prevent resin from running out before it gels [Figure 3.4(c)]. Repeat this method until the entire crack is filled, as indicated when additional resin is refused by the crack.
4. After curing (approximately 24 hours) the nipples are cut off from the crack, providing a smooth, even surface [Figure 3.4(d)].

Epoxy resin injections have been successfully employed in the repair of delaminated bridge decks (Crompton *et al.*, 1974). It is important to remember that the effectiveness of the repair process is dependent on the ability of the epoxy resin to penetrate, under appropriate pressure, into the fine cracks of the damaged concrete (Chang, 1981).

The limitation of epoxy resin injection is that it can be used successfully only in non-moving structures. The repair can return a substrate to its original design strength but will not increase its load-bearing capability (SWRI, 1995).



**Figure 3.4** Repair of vertical cracks: (a) injection nipples inserted along the crack; (b) surface sealant applied over the crack; (c) injection of epoxy system into the crack via the nipples, showing a capped nipple after injection has been completed; (d) nipples have been removed and the surface sealed

## 3.6 Epoxy coatings

### 3.6.1 Resistant coatings

Epoxy coatings are considered a versatile choice for the construction industry because of their excellent adhesion to concrete, steel and metal surfaces and their chemical resistance, toughness and corrosion resistance. A variety of brands are marketed by manufacturers for different end-uses. In general, the protective purpose of these coatings is resistance to corrosion and chemical attack.

Epoxy coatings for the construction industry are high build, solventless compositions with 100% solids. They are available in a large range of colours and shades. The performance is excellent for indoor applications.

They are not suitable for use as architectural finishes on exterior exposures because of their tendency to yellow and chalk on exposure to weather and sunlight.

The binders used in these ambient-cured formulations are generally low molecular weight reactive epoxy resins. These are cured with either amine or amine adducts to give the best chemical resistance, or with polyamide to give better water resistance, weathering and recoating properties (Dow Chemical Company, undated a).

High-solids epoxy coatings can be applied at dry film thickness (dft) between 200  $\mu\text{m}$  and 1000  $\mu\text{m}$  in one or two coats.

The general chemical resistance offered by these coatings makes them suitable for application in environments involving storage of aqueous mediums, aviation fuel, unleaded gasoline and many hydrocarbons (International Paints, 1996). Resistance to chemicals depends upon the type of curing agent used.

It is possible to use glass fibre reinforcements in order to increase the thickness or, where necessary, to bridge fine cracks in the substrate. Some coatings are also formulated to be used on damp concrete surfaces which cannot be dried.

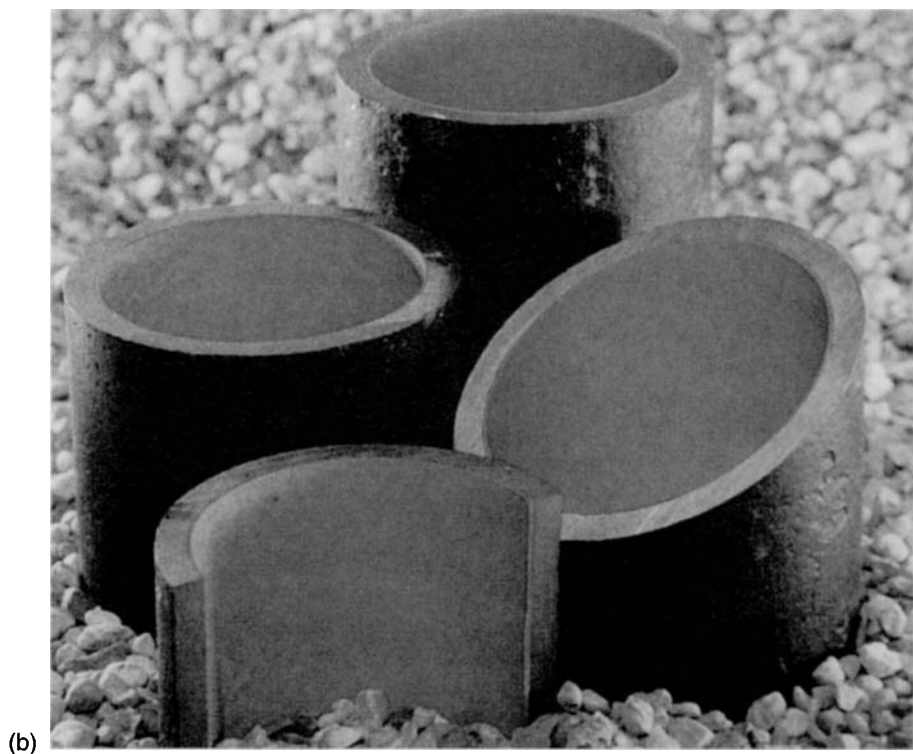
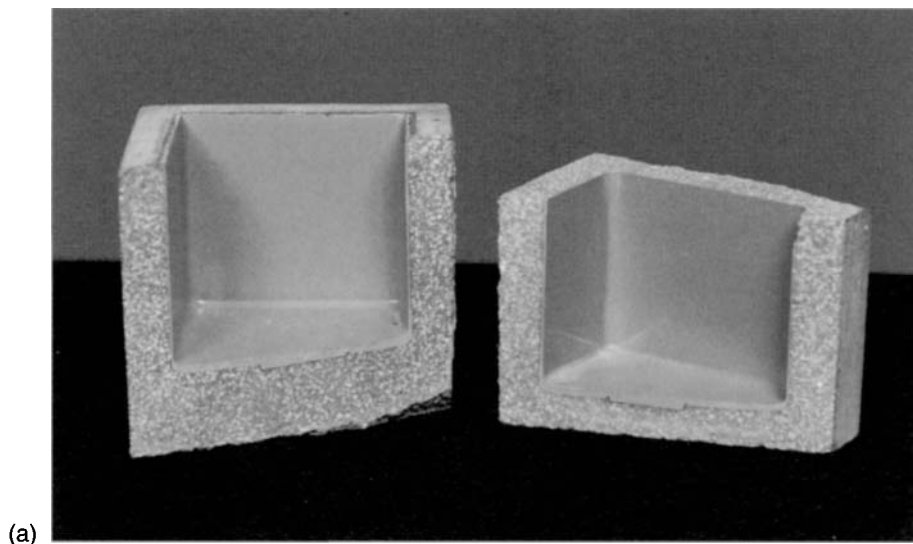
Specific applications of epoxy coatings are potable water tanks [Figure 3.5(a)], internal linings for pipes [Figure 3.5(b)], reservoirs, water-treatment works, grain silos, dairies, meat and food processing plants, the beverage industry, bottling plants, sewage works, laundries, dye works, food processing kitchens and so on.

It is also possible to formulate epoxy coatings by using glass flakes. This improves the abrasion resistance. Such coatings can be applied at a dft of between 1500  $\mu\text{m}$  and 3000  $\mu\text{m}$  (International Paints, 1996).

Apart from good mechanical properties and chemical and corrosion resistance, another advantage of solventless epoxy coatings is that there is no emission of solvents and less of a possibility of contamination, making them more environmentally friendly than other options. Ecological concerns have led to increasing use of these materials.

The drawback of these coatings is their short pot-life and their sensitivity to humidity (Sherman *et al.*, 1982). Attempts have been successful to overcome the problem of short pot-life. This improvement is possible with use of special spray equipment in which base and hardener are added in separate chambers. On application, both the components are forced through a single nozzle and are well mixed. Another approach to overcome the short pot-life problem is to develop curing agents that give a long pot-life compared with conventional systems. However, this approach is successful only in tropical climatic conditions; in countries with cold climates such coatings suffer from long curing periods.

Properties of epoxy coatings are given in Table 3.3.



**Figure 3.5** Examples of applications of epoxy coatings: (a) sample section of a potable-water tank; (b) internal linings for pipes. Reproduced with permission from Fosroc

**Table 3.3** Properties of epoxy coatings

Abrasion Resistance	Good
Physical Properties	Hard, Tough and Rigid
Flexibility	Good
Impact Resistance	Good
Chemical Resistance to:	
Alkalis	Excellent
Acids	Good
Solvents	Fair to Good
Resistance to Ultraviolet Radiation	Fair
Volatile Organic compounds	Very low to none

### 3.6.2 Epoxy laminate coatings

There are solvent-free systems with 100% solids principally used as protective coatings for concrete or metal storage tanks. Such coatings are unpigmented, clear compositions. They are thixotropic and can be applied both on horizontal and on vertical surfaces.

The two-pack coating contains epoxy resin base in one pack and curing agent in another. Primers are recommended by most of the manufacturers. Depending upon the requirement of increased build, it can be used with or without glass fibre reinforcement. The reinforcing glass cloth reduces shrinkage and strengthens the lining. The glass fibre is sandwiched between two layers of coating. After curing, such reinforcement is visible (Figure 3.6). A successful laminate coating must be impermeable, soft as well as tacky so that the glass fibre reinforcement should hang without slumping on a vertical surface. The cloth must have a fairly open weave so that some resin extrudes through the opening when rolled or pressed into the base coat (Maslow, 1982). This will increase the bond between base coat and cloth.

It is impossible to achieve a dft between 400–500  $\mu\text{m}$  in two coats without fibre glass reinforcement. In some laminate systems, glass flakes are also used as fillers. Their function is to minimise the shrinkage stress.

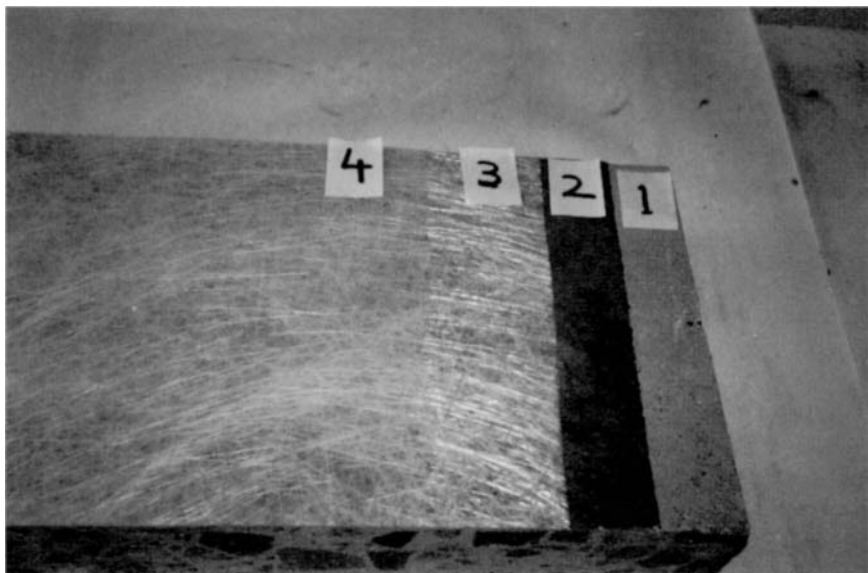
The cured coating has excellent chemical and abrasion resistance. Specific areas of application are storage tanks in refineries and oil fields, water purification units, the paper industry and for reservoirs and tunnels.

It is important that only experienced contractors install this system. Fibre glass should be handled carefully because the tiny fibres may break up and enter the skin and cause discomfort.

### 3.6.3 Epoxy-tar coatings

Coal tar epoxy coatings are formulated by using liquid or solid epoxy resins. A variety of curing agents can be used; for instance amines, amine





**Figure 3.6** Sample showing the pattern of epoxy laminate coating: 1 = uncoated surface; 2 = first coat; 3 = glass fibre reinforcement; 4 = top coat to form a sandwich. Reproduced with permission from Fosroc

adducts, polyamides and isocyanites. These systems are considered to be a fortunate combination of two materials. The epoxy improves the thermal plasticity and weather resistance of the coal tar, and the coal tar improves the water resistance of the epoxy (Munger, 1982). Choice of coal tar pitch plays an important role in a good coal tar-epoxy coating.

These coatings are based on two-component systems consisting of pitch, epoxy resin base and a curing agent. In some instances it may be desirable to formulate an epoxy resin base and a curing agent blended with the tar. This particularly applies when ambient temperatures are high, as under such conditions mixtures of pitch and epoxy resin tend to react, giving an increase in viscosity. However, this is not true in all cases.

There are three basic types of coal tar-epoxy coating:

1. solvent-based coatings prepared from solid epoxy resins (of epoxide equivalent weight 500);
2. solvent-based coatings prepared from liquid epoxy resins;
3. high-solids coatings prepared from liquid epoxy resin.

Non-solvented coal tar-epoxy coatings are in wider use.

Coal tar-epoxy coatings are resistant to a wide range of chemicals and chemical solutions, including freshwater, seawater, distilled water, sewage, detergents, dilute mineral acids and alkalis, barnacle growth, exhaust

**Table 3.4** Properties of coal tar–epoxy coatings

Physical Properties	Excellent flexibility, impact resistance, abrasion resistance and hardness
Chemical Resistance	Excellent
Weather Resistance	Reasonable
Bacterial Resistance	Excellent
Adhesion	Excellent to concrete and metal without primer
Protective Properties	Protect concrete and metal from corrosive environments
Unsuitability	For gasoline and hydrocarbon fuel tanks

gases, marine bacteria and brine. Resistance to ketones and low boiling aromatic hydrocarbons is unsatisfactory. Weather resistance is reasonable, with loss of gloss after a long period.

Coal tar–epoxy coatings are extremely durable and can be used for the protection of concrete and metal against severe corrosive action in submerged and non-submerged conditions. These coatings adhere excellently to concrete, metal or wood without the use of primers. Also they have excellent flexibility, impact resistance, abrasion resistance and hardness. The softening point of such coatings is usually in the range of 200°C–300°C, which makes them suitable for use at elevated temperatures.

Particular applications of coal tar–epoxy coatings related to concrete and metal protection include tank linings, pipes, foundations in aggressive soils, manholes, sewage works, effluent plants, chemical processing plants and dock and harbour installations.

Coal tar–epoxy coatings are not suitable for use as a tank lining material for gasoline and other hydrocarbon fuels as they tend to discolour clean fuel by a leaching process (Sherman *et al.*, 1982).

General properties of coal tar–epoxy coatings are listed in Table 3.4. Legislation in many countries is leading towards the search for suitable alternatives to coal tar, which is considered to be carcinogenic. Albino coal tar modifiers appear to be suitable for the job (Hunt and Ashcroft, 1994).

### 3.7 Epoxy floorings

Concrete floors do not offer all the properties needed for some applications. For example they do not fulfil the criteria of high strength, abrasion resistance and chemical resistance essential for a good industrial floor. Resin flooring has been found to be successful under these conditions. Among various resin floorings epoxy floorings are being widely used in the form of floor screeds, self-levelling floors, floor coatings and terrazzos.

Epoxy floorings consist of base, curing agent and filler as separate components. These are mixed on site before application. They are applied

## **4 Polyurethanes in the construction industry**

### **4.1 Introduction**

Remarkable advances have been made in the past two decades in polyurethane technology. Advanced technologies geared to the needs of today's construction industry ensure effective protection for concrete structures. The properties that make polyurethanes useful in construction applications are:

- excellent bonding;
- good tensile strength;
- flexibility;
- hardness;
- abrasion resistance;
- oil and solvent resistance;
- resistance to ultraviolet light and to ozone.

The various technologies offered to the construction industry are protective coatings, sealants, floorings, waterproofings, adhesives, insulating foams and leak sealers or crack-injecting systems. Recent environmental regulations in many countries have led to carefully targeted research and development on water-borne polyurethanes in which environmental protection forms an integral part of production processes and their applications. Table 4.1 summarises the principal properties that are useful for a particular product and Table 4.2 outlines the general properties of polyurethanes.

### **4.2 Polyurethane sealants**

Polyurethane sealants have taken a good share in today's sealant market. Polysulphide sealants are in greater use for water-retaining structures, and silicone sealants for structural glazing purposes; but polyurethanes have a greater market share as construction sealants. These sealants were first introduced to the construction industry in the early 1970s as two-component materials.

Polyurethane sealants are available as in both single-component and multicomponent formulations and in each case a variety of performance

**Table 4.1** Principal properties, products and application areas of polyurethanes

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Sealants, for construction joints:
retention of movement capability
high tear strength
good recovery
weathering resistance
range of colours
Coatings, for protection of concrete and metals:
protection of concrete from de-icing salts and other chemicals
ability to control water absorption
adhesion
suitable for interior and exterior application
long-term retention of colour and gloss
flexibility
Adhesives, for bonding wood-based housing components:
excellent bonding
different degrees of flexibility
Waterproofing systems, for a wide range of waterproofing applications:
fast curing
thermal stability
seamless
chemical resistance
stable to oxidation
excellent bonding
Leak sealer or crack-injecting systems, for cracks where movement is anticipated:
impermeable to water
elastic
flexible
suitable for application in dry as well as damp conditions
Foams, for insulation in buildings:
low thermal conductivity
low density
low moisture permeability
excellent dimensional stability

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**Table 4.2** General properties of polyurethanes

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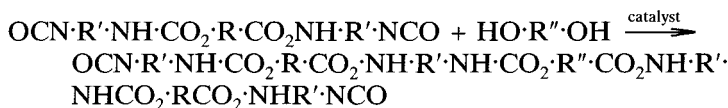
Property	Value
Hardness range (shore A)	10–100
Tensile strength (MPa)	up to 70
Tensile strain at break (%)	500–1000
Service temperature (°C)	–20 to 80
Heat resistance	Moderate to excellent
Cold resistance	Moderate
Tear strength	Excellent
Abrasion resistance	Very good
Sunlight resistance	Excellent
Ozone resistance	Very good
Flame resistance	Medium
Chemical resistance	Excellent
Limiting properties	Poor moist and heat resistance

---

qualities is available. These sealants can also be designed to be self-levelling for horizontal applications and non-sag for vertical applications.

The basic reactive group in forming any urethane polymer is an isocyanate group which on reaction with a hydroxyl group yields a urethane group. For sealant polymers long chains containing hydroxyl groups are needed.

In two-component sealants the components consist of a base, a hydroxyl-terminated compound and a liquid isocyanate-terminated prepolymer. The prepolymer reacts with the base in the presence of a catalyst to form the polyurethane:



One-component polyurethane sealants are based on a polyether or polyester isocyanate prepolymer end-capped with a room-temperature-curable group such as trialkoxy silane. Free isocyanate groups are not used in one-part systems because carbon dioxide is evolved on reaction with moisture from the atmosphere which results in bulging of the sealant in the joint.

Two-component sealants set by direct chemical cure whereas one-component sealants involve a mechanism of direct moisture cure or moisture-triggered chemical cure. In building sealants quick cure is advantageous where the building elements will be subjected to strain shortly after the sealant has been applied. But if cure is too rapid, adhesion will be damaged in most cases. This is probably because the sealant does not have time to wet-out the underlying surface. In many cases in order to achieve good adhesion to substrates primers are required. Whether or not to prime will be given in the manufacturer's instructions.

Details of various joints are given in the discussion on polysulphide sealants (section 7.3) and silicone sealants (section 6.3). The same criteria are applicable in the case of urethane sealants, with the exception of glazing joints.

Polyurethane sealants are available in a non-sag formulation suitable for vertical joints and in a self-levelling formulation, useful for horizontal joints. The latter class of sealants flow into the joint giving a smooth level surface. They do not require tooling.

Good urethane sealants:

- are resistant to minor vandalism;
- are odourless;
- have a high tear strength;
- have a good resistance to puncture;
- have good oil and solvent resistance;
- possess excellent resistance to ultraviolet light and ozone;
- possess good recovery and have a good retention of recovery;

- possess good retention of movement capability;
- give optimum resistance to compression set.

Owing to the use of a wide variety of polymers reacted with various isocyanates, the properties of polyurethane sealants vary considerably (Woolman, 1994). One-part sealants have a movement accommodation factor in the range of 10%–30%, and that for two-part sealant ranges between 20%–30%. The life expectancy for polyurethane sealants is 20–25 years in general. Hardness, as measured by the shore A method, ranges between 15 and 30. It should not exceed 40 with heat ageing or with extended time. In the case of self-levelling sealants, which are designed for horizontal applications, the sealant is formulated to have a minimum shore A hardness of 25 (Table 4.3).

One-component and two-component polyurethane sealants each have particular advantages. The main advantage of a one-component sealant lies in the fact that no mixing is required. One-component materials are considerably easier to use on high-rise buildings. Two-component sealants have the advantages of infinite package stability, the possibility of a wide colour range and the possibility of quick cure.

**Table 4.3** Properties of one-component and two-component polyurethane sealants

	Two-component	One-component
Ingredients	<i>Base component:</i> Polyurethane prepolymer, inert fillers, pigments, non-prepolymers, volatising plasticisers <i>Curing agent component:</i> Polymerising agents, activators, accelerators, extenders	Polyurethane, inert fillers, pigments, non-volatising plasticisers
Curing mechanism	Chemical reaction with curing agent, leading to uniform cure; rate is influenced by temperature and humidity	Chemical reaction with moisture in air; forms a skin; then cures slowly inward
Hardness (shore A)	15–40	15–40
Resiliency	Very high	High
Recommended joint movement (%)	20–30	10–30
Puncture and tear resistance	Excellent	Excellent
Life expectancy (years)	20+	20+
Applicable specifications	TT-S-00227 E, 19-GP-15 (Canadian), 19-GP-16 (Canadian), ASTM C-920, ISO 11600	TT-S-00230C ASTM C-920 ISO 11600

The exceptional stability of the urethane bond results from thermodynamic determinants of bond strength, from the crystallisation that results from the structure of both the polyol and the strongly hydrogen bonding urethane and from cross-links that result from the formation of 'hard' chain segments (Evans and Greene, 1982).

#### 4.2.1 *Specific applications*

**4.2.1.1 Building and construction sealants.** Polyurethane sealants are available with low as well as high moduli. Low-modulus non-sag building sealants are suitable for sealing expansion and other movement joints in building structures (Figure 4.1), including those between lightweight cladding panels, precast concrete panels (Figure 4.2) and junctions between components. Such sealants have a movement accommodation factor of 25% of the average joint width.

High-modulus non-sag sealants are useful for lightweight building components, rim and rebate sealing of ventilation ducts, rolling stock and cladding jointing of ceramic tiles, pipe entries, unions and sleeves (Figure 4.3). These sealants are not suitable for jointing between precast panels.

Self-levelling polyurethane sealants are used to seal horizontal movement joints and construction joints in a variety of materials subject to light traffic such as concrete pavements (Figure 4.4), access roads, yards, parking areas, between rails and metal enclosures and around equipment and machinery.

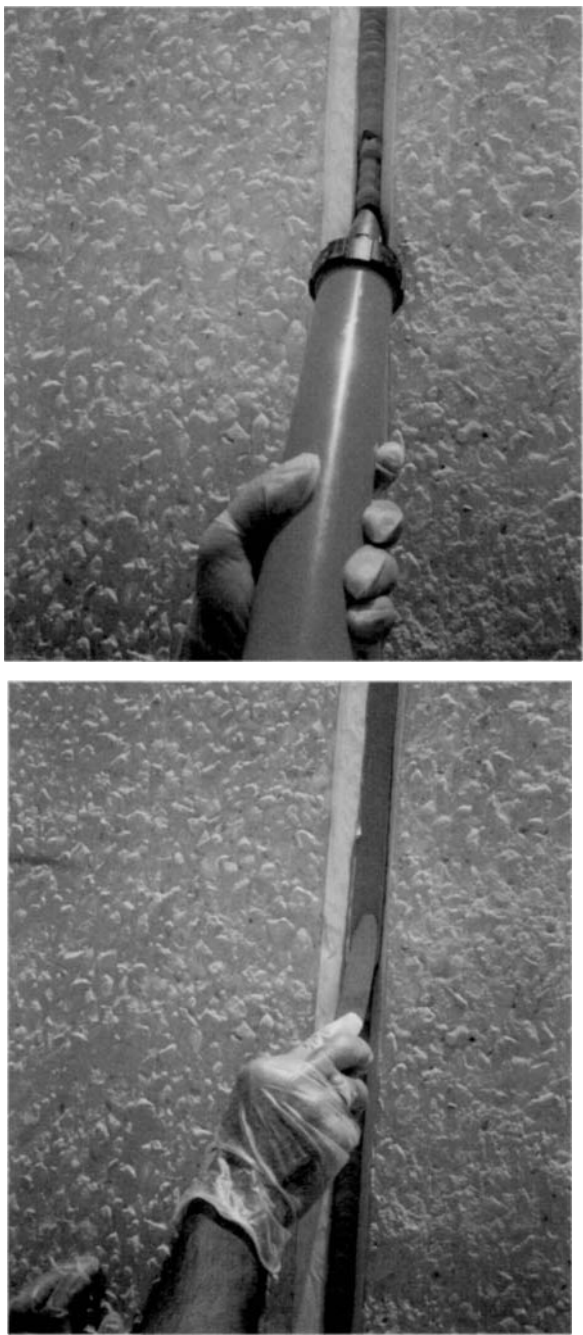
**4.2.1.2 Pitch-polyurethane sealants.** Polyurethane sealants can be formulated in combination with pitch or coal tar in order to impart the property of fuel and oil resistance. Such sealants comply with British Standard BS 5212 and US Federal specification SS-S-200E.

Pitch polyurethane sealants are suitable for areas subject to fuel and chemical spillage. Such sealants also resist biodegradation in sewage treatment plants. It is important to mention that non-biodegradable sealants are also being marketed as a specific sealant. Such sealants find use in sewage treatment plants, effluent pits, drainage channels, retaining walls, tunnels and sewers.

Fuel-resistant sealants are used for sealing and maintaining joints in concrete roads, runways, hard standings, storage depots, parking bays, garage floors, car washing bays and car parks. Such sealants perform well over a broad temperature range, possess resistance to a variety of chemical solutions and resistance to micro-organisms.

#### 4.2.2 *Merits and demerits*

The merits of polyurethane sealants are as follows:



**Figure 4.1** The use of non-sag polyurethane sealants in an expansion joint: (a) application; (b) tooling. Reproduced with permission from Fosroc





**Figure 4.2** Precast joints applied with polyurethane sealant. Reproduced with permission from Fosroc

- they handle wide joints and large movement without failure;
- they have excellent resistance to penetration when used in horizontal traffic-bearing areas;
- they have excellent adhesion to and compatibility with a wide variety of construction substrates;
- they have a wide range of joint-movement capabilities combined with excellent elongation and recovery properties;
- fast cure is possible for two-component systems;
- they have excellent resistance to compression set and notch propagation;
- they show excellent tear resistance;
- a broad range of cure hardness is available;



**Figure 4.3** High-modulus polyurethane sealant being applied to pavement joints between granite. Reproduced with permission from Fosroc

- there is negligible shrinkage;
- they have excellent ultraviolet and ozone resistance.

The demerits of polyurethane sealants are as follows:

- they require more priming;
- they are not suitable for wet joints;
- one-component sealants are not recommended for traffic areas;
- they are not recommended for structural glazing;
- only limited elevated temperature properties are possible;
- a variety of formulations can cause wide differences in performance between brands.



**Figure 4.4** Application of self-levelling polyurethane sealant to a pavement joint. Reproduced with permission from Fosroc

### 4.3 Polyurethane coatings

Polyurethane coatings have good adhesion to concrete and in many situations protect it from deterioration by controlling the water absorption and passage of vapour; two-part polyurethane coatings arrest the process of acid attack. They cope well with relatively dilute acids (Edwards, 1993b).

The American Society of Testing and Materials (ASTM) has classified polyurethane coatings into five categories, as given in Table 4.4.

Among these five types, types 1, 2 and 5 are most commonly used as floor coatings. The two-component coatings (especially type 5) give best results because of ease of pigmentation. Such coatings exhibit resistance to many chemicals and solvents. They also give good abrasion resistance.

**Table 4.4** The American Society of Testing and Materials' (ASTM's) classification of polyurethane coatings

ASTM type	Curing mechanism	Pigmentation	Number of components
1	Air-cured	Conventional	one
2	Moisture-cured	Difficult	one
3	Heat-cured	Conventional	one
4	Catalysis	Difficult	two
5	Polyol-cured	Pigments in polyol	two

Moisture-cured coatings (type 2) are suitable in areas where high impact, tensile and flexural strengths are desired. They are generally used on seamless floorings to provide a final glaze system. They can also be applied as a flooring as the glaze finishes to a tile-like system. Such systems are generally used in industrial environments.

Polyurethane surface barrier systems have been used to protect concrete from de-icing salts and other chemicals. They have also been used to prevent fungal growth on concrete and to protect against wind-driven rain while lending self-washing properties. When urethanes are mixed with long-lasting decorative paint, they can be used to mask concrete discoloration (ACI, 1985). As conventional coatings they are quite often applied over very fine cracks to prevent ingress of water and carbon dioxide. Such coatings are flexible, with an ability to bridge fine cracks, which do not have any structural significance. Methods have been deployed to cover cracks in some offshore structures which would otherwise have been subjected to chloride attack. Conventional polyurethane coatings have also been used to protect concrete affected by alkali silica reaction (Edwards, 1993b).

Polyurethane coatings can be used for remedial applications in sewers and effluent-treatment plants, but they are suitable for milder conditions only. Two-pack polyurethane coatings are employed in this case. However, difficulties may be encountered during application if the system is sensitive to surface moisture. Polyurethane coatings in such applications need several coats to attain the necessary film thickness.

Polyurethane coatings are also used as tank linings for effluent trenches and buffer tanks, which have great variations in pH. They are suitable in such applications only under less severe conditions.

In the form of reinforced coatings, polyurethane systems may be more suitable because they exhibit fewer problems with solvent entrapment. The fibre-reinforced systems encountered tend to be used for repairing badly cracked liquid-retaining structures. The reinforcement allows the coating to bridge cracks and the typically high film thickness (3–5 mm) ensures that under normal circumstances there can be no passage of liquid. Additionally, because of the high tensile strength of the material, it provides resistance to cracking if the structure is subject to thermal movements.

Two-component polyurethane coatings offer several advantages:

- they offer durable, seamless protection of concrete and metal;
- they have high resistance to tensile, compressive and shearing forces;
- they possess resistance to aggressive media, microbes, weathering and root penetration;
- they are resistant to high and low temperatures, with elasticity unaffected by extreme climatic conditions.

A balanced spectrum of performance properties makes them suitable for applications ranging from bridges, roofs, outdoor stairways and terraces to underground and multi-storey car parks, tunnels and all types of industrial plants.

In general, polyurethane coatings have good chemical resistance and excellent impact and abrasion resistance. They are hard and flexible, with good adhesion characteristics. They are suitable for interior as well as exterior applications, with long-term retention of colour and gloss.

In view of the several brands available in the market, which show wide latitude of formulation, it is necessary to go through the application and end-user recommendations of the manufacturer.

#### **4.4 Pitch-polyurethane coatings**

These coatings are similar to pitch-epoxy coatings (section 3.6.3) in most aspects. They have some advantages over pitch-epoxy coatings: they are more flexible, they have excellent resistance to outdoor weathering and show less chalking and cured coatings exhibit almost identical properties to similar paints at higher ambient temperatures.

Pitch-polyurethane coatings are two-component materials containing polyol as the base resin and an isocyanate curing agent. They cure satisfactorily at temperatures as low as 0°C (BSC, undated).

Like pitch-epoxy coatings, pitch-polyurethane coatings are excellent materials for use under very corrosive conditions such as for sewage work, marine and port installations, chemical works and power stations. Particular applications are for:

- underground storage tanks;
- building works below ground level;
- water storage tanks;
- indoor and outdoor structural steel;
- tanks or equipment in corrosive chemical fumes or spillage areas;
- marine pilings.

Pitch-polyurethane coatings should not be used without obtaining specific recommendations from the manufacturer for the particular application being considered.

#### **4.5 Polyurethane floor toppings**

Polyurethane floor toppings are usually one-component moisture-cured materials, applied on concrete floors to prevent dusting. They are applied

in two coats to give a durable, decorative, non-slip surface. They are also used in conjunction with coloured flakes. Such flakes can be made of different materials, such as marble chips, metallic flakes and vinyl flakes. Vinyl flakes have wider use. Such flakes are inert towards polyurethane resins and solvents used in the system.

Application of this seamless system involves the following steps:

- treatment of area with decorative chips;
- application of polyurethane glaze, either by spray or by roller;
- a second application of chips while the above coat is tacky to provide a three-dimensional effect;
- the above coat is allowed to dry until it is possible to walk on it with polyethylene-covered shoes;
- removal of excessive chips by light sanding followed by vacuum;
- sealing of the floor with two or more coats of polyurethane glaze, with a minimum amount of drying time between each coat.

Dry conditions are necessary at the time of application in order to achieve best results.

## 4.6 Polyurethane adhesives

### 4.6.1 *Two-component adhesives*

Two-component polyurethane adhesives are the condensation product of a polyol with an organic isocyanate. The first component contains a prepolymer of the polyol, and polyisocyanate is the second component. These two components are thoroughly mixed before application.

By altering the molecular architecture of the two components, that is, by providing different degrees of chain flexibility, and controlling the number of sites for subsequent urethane formation a wide range of mechanical properties can be obtained in the final polymer, ranging from very soft and deformable adhesive films to very rigid films (Richard and Charles, 1977).

The two components cure without evolution of any by-products, little or no volume change occurs and the system is ideally suited for use in thick and variable thickness bondlines. Solventless and 100% solid systems are possible which cure at room temperature within a few minutes. Viscosity, curing rate and cure temperature requirements can be tailored to meet the user's needs. Application of the system is generally made by two-part metering and mixing equipment.

The main application of two-part polyurethane adhesives is for rapid bonding of wood-based materials, particularly for the assembly of housing components (Figure 4.5).



**Figure 4.5** Polyurethane adhesives used in housing components for bonding plywood

#### *4.6.2 One-component adhesives*

These are moisture-cured materials used for joining porous materials. Porous conditions are needed for at least one material for this adhesive to work. They are totally unsuitable for any non-porous materials because the solvents present could not escape and moisture could not reach the surfaces of the polymer for cure (Kumar and Kumar, 1982).

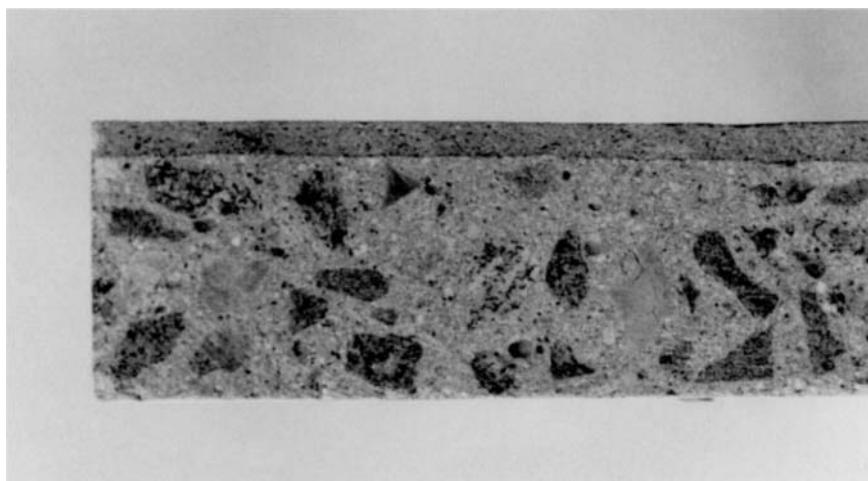
This type of system may be used as a bonding agent for marine-grade plywood. Other applications are for laminated wood beams and wood doors.

### **4.7 Polyurethane floorings**

Heavy-duty polyurethane floor screeds are used mainly as industrial floors. These are multicomponent materials containing base, hardener and aggregate in separate packs. A range of colours is possible. Most of the commercially available systems are fast curing. Such systems resemble epoxy floor screeds. They can be applied at thicknesses between 5 mm and 12 mm over concrete (Figure 4.6), with a minimum compressive strength of 25 N/mm<sup>2</sup>. It can also be applied on polymer-modified sand-cement screeds. Priming of the substrate is essential to ensure thorough adhesion.

Salient features of polyurethane floor screeds are:

- resistant to thermal shock;
- high abrasion and impact resistance;
- slip resistance even in wet conditions;



**Figure 4.6** Section showing the application of polyurethane floor screed on a concrete base.  
Reproduced with permission from Fosroc

- suitable for use in wet process conditions;
- easy cleanability;
- dirt and bacteria ingress prevention;
- excellent chemical resistance.

Many manufacturers claim excellent resistance to dilute mineral acids, caustic solutions, bleaching agents, weak solvents and organic acids at ambient temperature. Resistance to organic acids is of particular importance as this property is not possible with epoxy systems, except for those cured with aromatic amines, a dying practice in view of recent legislation. Thus, it may be beneficial to use polyurethane floorings where resistance to organic chemicals is desired, but it is important to consult the manufacturer before making a final selection.

Use of polyurethane flooring is generally not suitable on surfaces which suffer from rising damp or which have a relative humidity greater than 75% as measured in accordance with BS 8203 appendix A. In view of their fast curing properties, such systems are useful in cold climatic conditions.

Typical areas of application include the food-processing industry, drink and beverage production areas, dairy processing and the pharmaceutical industry.

#### **4.8 Polyurethane waterproofing systems**

In this section the discussion is focused on liquid-applied elastomeric membranes. Two-component and one-component systems are available,



but the latter type is more widely used. Liquid-applied polyurethane waterproofing systems minimise many of the problems inherent in sheet materials; that is, they achieve an immediate bond to the substrate and the concrete topping bonds to the membrane while it is still tacky.

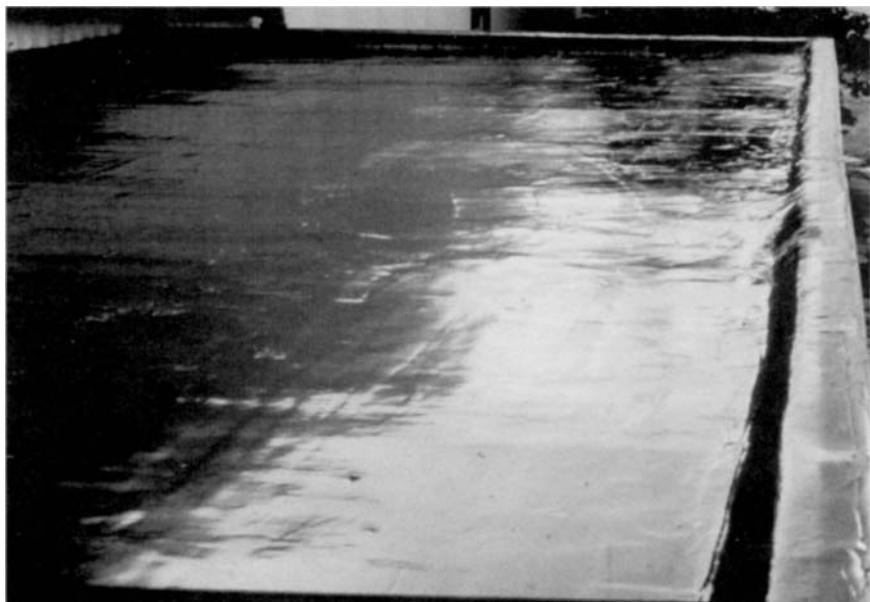
Liquid polyurethane waterproofing systems are coal-tar modified products. Two-component materials are catalysed curing systems, and one-component materials are cured by exposure to moisture. Both the materials exhibit comparable properties on complete curing. Two-component materials require on-site mixing of the components. One-component materials can be applied directly, but the problem with this type is polymerisation of the product inside the container if it is improperly sealed. Such products are purged with an inert gas when the pack is sealed.

Liquid waterproofing membranes are applied on smooth and, in most cases, on primed surfaces. Primers are based on two-component epoxy-polyamide systems. Application is made by pouring the material onto the substrate, followed by spreading with a squeegee or a trowel. In the case of large areas, spray equipment may be used. The membrane is generally allowed to cure for at least 12–14 hours at ambient conditions, and then concrete may be placed upon it. The material exhibits tough, rubber-like properties on cure. A range of grades is supplied by manufacturers to meet all site application methods and requirements.

Liquid-applied polyurethane waterproofing membranes have several advantages, as follows:

- ease of application – they can be brushed, rolled or sprayed onto the surface;
- fast curing – they cure within an hour of application, enabling large areas to be covered in a working day;
- excellent adhesion to concrete and many other substrates;
- imperviousness;
- thermal stability – they cure by irreversible chemical reaction, eliminating melting and flow at high temperature.
- weathering resistance – they are resistant to ultraviolet light and do not embrittle;
- non-oxidising – they are stable to oxidation;
- chemically resistant – they have a great resistance to general chemicals, certain solvents and engine fuels;
- seamlessness – there are no joints in the membrane;
- spot repairs – mechanical damages to membranes can easily be repaired by spot application of the product.

The high elasticity, low water permeability and excellent bonding make liquid polyurethane systems suitable for a wide range of waterproofing applications such as for foundations, basements, tunnels, multilevel



**Figure 4.7** Elastomeric polyurethane waterproofing membrane on a roof terrace. Reproduced with permission from Fosroc

parking garages, roof decks, bridge decks, water-retaining structures (not suitable for drinking water), sewage works, inverted roofs and roof terraces (Figure 4.7). They are also used for waterproofing subways and tunnels, swimming pools, planters, gutter and pipe repairs and for wall and roof joints.

Non-sag grades are available for vertical applications. The dry film thickness of the system is approximately 1 mm.

#### **4.9 Polyurethane roof coatings**

Polyurethane roof coatings are 100% solid formulations and are available in almost all colours. The long-term durability and reasonable properties provided polyurethane roof coatings a prominent position in the roofing system in the 1980s. However, with the emergence of acrylic roof coatings, the use of polyurethane systems has gone down to some extent.

Polyurethane roof coatings can be applied by trowel (Figure 4.8), squeegee or by spray. The product is supplied in two components. It may be used on areas exposed to traffic as well as non-trafficked roofs. The thickness of the cured system is approximately 1 mm.



**Figure 4.8** Trowel application of polyurethane roof coating

Properly formulated systems exhibit the following properties (Maslow, 1982):

- they maintain flexibility under extreme weather conditions, from 30°C to 93°C;
- non-structural concrete cracks can be bridged without rupturing;
- leakage is prevented with a continuous elastomeric membrane, providing optimum waterproofing;
- the substrate is protected from deterioration spalling and freeze/thaw damage;
- surfaces are protected from deterioration from gasoline, oil, battery acid, de-icing salts and other chemicals associated with automotive traffic;
- they have a low maintenance cost – damaged areas may be repaired easily with the same compound by brush or trowel.

Polyurethane roof coatings are applied on roof decks, parking decks, ramps and walkways.

#### 4.10 Polyurethane leak sealers and crack-injection systems

It has been mentioned in section 3.5 on epoxy crack injection systems that epoxies do not do well in wet conditions because they resist movement. Polyurethane resins are suitable for injection of cracks in concrete or masonry in dry or damp conditions. They can be successfully applied in cracks having a width in excess of 0.2 mm. On curing they form an elastic seal impermeable to water.

As with epoxies there are many different polyurethanes available, but unlike epoxies, polyurethanes are classified into two categories: hydrophilic and hydrophobic. Both react with the water present in a crack substrate to create a chemical reaction that causes the material to expand into a gel or foam that fills the void with a tight seal. Some polyurethanes are so elastic they can stretch by as much as 750% (*Applicator*, 1995).

Polyurethane crack-injection systems have a lower compressive strength than the epoxy equivalent and are designed to waterproof a substrate not for structural repair. They allow for future movement at joint locations but add little to the overall strength of the wall. Hydrophilic polyurethanes suck up water into a crack until they can hold no more and repel the rest, much like a sponge. Hydrophobic polyurethanes take what they need from hydrogen and oxygen molecules to begin a chain reaction and repel the rest of the water, exerting greater force against it.

Polyurethane crack-sealing systems have a low viscosity. They penetrate into fine cracks and cavities. Cured systems have strong but flexible characteristics, to withstand differential structural movement. They also withstand high hydrostatic pressures.

Application of the product is made by standard resin-injection equipment, having a minimum injection pressure of  $0.4 \text{ N/mm}^2$  (4 bar). The method of application is almost the same as that of an epoxy crack-injection system.

In order to seal cracks in wet conditions hydrophobic systems are used in conjunction with a hydrophilic polyurethane resin system. These are rapid foaming and setting resins which stop the flow of water when injected into cracks in concrete in the presence of moving water, providing an effective system of crack sealing in wet conditions. As soon as the hydrophilic resin stops the flow of water, the hydrophobic resin can be reinjected to produce a permanent seal.

Polyurethane crack-sealing systems are two-component, solvent-free materials. They are available in a range of viscosities and can be used to combat low-volume and high-volume leakage with equal success (Edwards, 1993a).

#### 4.11 Polyurethane foams in the construction industry

Rigid polyurethane foams are used in the building industry mainly as insulating material. These are based on low molecular weight polyols and diisocyanates, such as diphenylmethane diisocyanate, in order to increase cross-link density and stiffness. Intermediate degrees of stiffness can be obtained by varying the formulation. Rigid foams containing isocyanurate groups are also made by trimerisation of polymeric isocyanates in the presence of polyols and a blowing agent (Manson, 1984).

Rigid urethane foam is recognised as an outstanding material for insulation application. It has desirable properties, such as (Kaplan, 1969):

- low thermal conductivity;
- low density;
- excellent dimensional stability;
- high strength-to-weight ratio;
- low moisture permeability;
- low water absorption.

There are three general methods of applying rigid urethane foam:

1. it may be poured in place, accomplished by a conventional or froth-foaming technique and is used for filling irregular voids with foam;
2. slab stock is used in applications where foam can be economically cut to the required shapes;
3. it may be sprayed in applications where mouldability is required.

The physical properties of rigid polyurethane foam are usually a function of the foam density. A change in strength properties requires a change in thermal insulation. In addition to density, the strength is influenced by the catalyst, surfactant, polyol, isocyanate and type of mixing used.

Chlorofluorocarbons (CFCs) were once commonly used as blowing agents. For years, pentane has become generally accepted as a blowing agent substitute for CFC. Pentane does not cause problems to the environment; with pentane an ozone-depletion potential does not exist (Polke, 1996).

In Western Europe 250 000 tons of rigid polyurethane foam were used for the production of sandwich panels in 1994. Owing to their outstanding mechanical and physical properties, these panels, produced in either a continuous or a discontinuous process and provided with flexible or rigid facing layers, have found a wide range of applications in the building industry (Esser, 1996).

Polyurethane rigid foam is an excellent insulation material, particularly well suited for applications requiring high mechanical properties. In the form of laminated boards, they are applied on roofs, ventilated façades, ventilated double walls, masonry construction, single-wall masonry interior walls, floors and ceilings and for floor heating systems.

Sandwich elements or composites with a core of polyurethane rigid foam are widely used for the construction of walls and façades as well as for roofs of industrial buildings, warehouses, cold storage facilities, supermarkets, airports, sports facilities, school buildings, garage doors and so on (Sommerfeld, 1996).

#### **4.12 Aqueous polyurethane systems**

Aqueous polyurethane systems have been developed which are considered to be safe from a health and safety point of view. They do not contain harmful isocyanates. The major application of this type of system is for coatings and floor finishes. Aqueous systems are based on single-pack, clear-water-based polyurethane. Two-pack and pigmented systems are also available.

They are flexible, exhibit excellent abrasion resistance, resistance to most household reagents and do not rely on mechanical sanding to achieve intercoat adhesion. These environmentally friendly systems address the issues of occupational health and safety in a market traditionally dominated by solvent-based coatings (section 2.3.8).

#### **4.13 Health and safety**

The information in this section has been abstracted from British Rubber Manufacturers Association Ltd (1977), Fire Protection Association (1972), Isothone Ltd (undated), Patty (1981), Pigott (1969), Sax (1984) and Sommerfeld (1996).

Presence of free isocyanate at levels above the minimum exposure limits may induce dermatitis, and inhalation may lead to respiratory problems. These symptoms, however, are cured by removing the cause. Polyurethanes do not involve any hazard as long as good standards of industrial and personal hygiene are practised.

Cured product dust at sufficient concentrations, however, constitutes a fire and explosion hazard and once ignited will burn fiercely.

Solvent-based products present fire hazards. Such products should be stored away from sources of heat and ignition. Solvent-free products present little or no fire hazard at normal ambient temperatures.

Grinding, cutting or milling of the cured products, producing dust or fine particles, can lead to the generation of static electricity, hence equipment for such operations, including dust extraction, should be properly earthed. Polyurethane prepolymers are commonly supplied as solutions in organic solvents. They therefore give off flammable vapours and present fire and explosive hazards. All polyurethane solutions should be used in well-ventilated, flame-proof areas. Smoking must be forbidden.

As with any chemical products, persons known to have a history of dermatitis, skin sensitisation or asthma should not work in direct contact with polyurethanes. Ingestion, inhalation, skin contact and eye contact should be avoided. Prolonged contact in any form with the skin may cause localised irritation leading to dermatitis and must be avoided. In case of skin contact, remove excess with clean cloth. Clean with proprietary cleansing cream and wash with soap and water. Do not use any solvent. Contaminated clothing should be removed immediately and not reused until it is laundered.

If the product is inhaled, the patient should be taken to fresh air, kept warm and, if recovery is not rapid, medical attention should be sought. Apply artificial respiration if necessary.

In the event of ingestion, do not induce vomiting, immediately seek medical attention.

In case of eye contact, irrigate immediately with copious quantities of water for at least 10 minutes and seek medical attention. Protective clothing, dust masks, gloves and goggles should always be worn during handling and application of all polyurethane polymers, compounding ingredients and finished products. It is necessary to clean hands with soap and water before consuming food or before going to the toilet.

A good standard of industrial hygiene should be observed where polyurethane prepolymers and their solutions are stored. Smoking and the preparation or consumption of food and drink must be prohibited.

All tanks and containers must be appropriately marked and during transportation they must be designated and documented so that sufficient information on the hazards and emergency procedures is always available.

Minor spillage should be absorbed with sand, swept up and placed in dry containers for disposal. Large spillages should be dealt with by sound engineering practice.

Where large quantities have to be disposed of, landfill or controlled incineration may be carried out with the approval of the local authority.

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## **5 Acrylics in the construction industry**

### **5.1 Introduction**

Acrylic materials based on methacrylates and emulsions have captured a good market share in the construction industry. The properties that are useful for construction applications are:

- excellent adhesion;
- flexibility and elongation;
- stability to ultraviolet radiation;
- carbonation resistance;
- environmental friendliness.

Table 5.1 outlines useful properties, products and application areas of acrylic systems. Key market segments are coatings based on methacrylates as well as emulsions and water-based sealants. Acrylic emulsions and redispersible powders as cement modifiers offer many useful products for several end-uses. However, the high cost of acrylic has limited their use as cement modifiers. The use of water-based acrylic systems is increasing because of their non-toxic and environmentally friendly nature.

Acrylic concretes and mortars are used in applications which require fast curing. Acrylic crack-injecting systems are suitable for wet cracks. Products such as adhesives, asphalt modifiers and floor-care polymers find only a small percentage of applications.

### **5.2 Properties**

#### **5.2.1 Adhesion**

Acrylics exhibit excellent adhesion to substrates such as concrete, masonry and wood. The majority of acrylic products are applied without using primer and give satisfactory adhesion. The more flexible resins give superior adhesion within the family of acrylic resins. The adhesive qualities of individual resins vary both with flexibility and with functionality.

**Table 5.1** Specific properties and applications of acrylic systems in the construction industry

Product and properties	Application area
Emulsion sealants: low cost one component environmentally friendly	light construction internal joins, fixtures and filling
Solvent-based sealants: one-component non-staining good weathering good chemical resistance	perimeter pointing cladding pre-cast joints
Acrylic polymer concrete and mortars: fast curing good chemical properties	patch repairs
Acrylic polymer crack injection: low viscosity in uncured state high degree of penetration	cracks with width less than 0.3 mm wet cracks
Methacrylate-based coating: resistance to ultraviolet radiation chemical resistance permeability to water vapour carbon dioxide resistance colour retention	anticarbonation coatings for concrete and masonry
Emulsion-based coating: elastomeric nature ability to bridge smaller cracks in concrete resistance to carbonation, sulphates and ingress of chloride ions	concrete and masonry structures
Acrylic-modified cementitious products: excellent bond strength water resistance resistance to ultraviolet radiation low water/cement ratio superior handling and application properties	various, depending upon type of product: repair mortars floorings tile adhesives renders coatings, etc.
Acrylic-modified asphalt: resistance to surface cracking, chalking and ultraviolet radiation flexibility oil and gas resistance	parking lots off-highway streets highway shoulders

### 5.2.2 Abrasion resistance

Higher molecular weight polymers have greater toughness and hence high abrasion resistance.

### 5.2.3 Hardness, flexibility and elongation

With the increase in number of carbon atoms in the ester functionality of the polymer there is a decrease in hardness and an increase in flexibility

and elongation in the case of straight-chain polyacrylates and polymethacrylates with  $C_8$  and  $C_{12}$  carbons, respectively.

Resins based on branched-chain esters have lesser elongation and greater hardness, whereas those from straight-chain or normal alcohol esters are softer and have higher elongation.

#### 5.2.4 Glass transition temperature

The glass transition temperature,  $T_g$ , is the temperature at which an amorphous material changes from a brittle glassy state to a rubbery state. Poly(methyl methacrylate) has the highest glass transition temperature ( $105^\circ\text{C}$ ) and poly(2-ethylhexyl-acrylate) the lowest ( $-55^\circ\text{C}$ ). Other predominantly acrylic polymers and copolymers lie between the two (Edward, 1968).

The glass transition temperature affects many of the properties of acrylic systems. An increase in this temperature will increase some properties and decrease others. The relationships are shown in Table 5.2.

#### 5.2.5 Solubility

This property depends upon the structure of the acrylic resin. Most of the resins are soluble in moderately hydrogen-bonded solvents (e.g. ketones, esters, chlorinated hydrocarbons and aromatic hydrocarbons). Resins with more alcohol chains have greater solubility in alcohols, aliphatic hydrocarbons and naphtha.

#### 5.2.6 Plasticisation

The purpose of plasticisation is to decrease hardness and to increase flexibility and elongation. Phthlates (e.g. butyl benzyl phthalate, dioctyl phthalate and butyl phthalate) are used as external plasticisers. Externally plasticised systems have a migratory tendency with ageing. In order to overcome this drawback, systems are being internally plasticised. This process involves the use of comonomers (e.g. acrylates and higher alkyl

**Table 5.2** Effect on physical properties of acrylics with increase in glass transition temperature

Properties which increase:	Properties which decrease:
brittle point	elongation
softening point	flexibility
hardness	tackiness
minimum film forming temperature	adhesion
tensile strength	blocking tendency
slip	

methacrylates) to soften the methyl methacrylate polymers. Internally plasticised systems exhibit permanent flexibility.

### 5.2.7 *Compatibility*

Acrylics, being polar in nature, are compatible with many polar resins. Molecular weight is an important factor in the compatibility of two resins, which should be approximately equal or somewhat lower. By virtue of this compatibility, properties can be improved and desired properties can be achieved; for example the flexibility and adhesion characteristic of acrylics can be improved by the addition of vinyl chloride polymers and copolymers.

### 5.2.8 *Stability*

Methacrylates are exceptionally stable to ultraviolet (UV) light and to oxygen owing to the absence of tertiary hydrogens on the polymer chain which prevent photo-oxidative and thermo-oxidative attack. Acrylate ester polymers are somewhat less resistant to both UV light and thermal oxidation owing to the presence of tertiary hydrogen atoms.

Acrylics in general are also resistant to acids, bases, weak and moderately strong oxidising agents and many corrosive industrial gases and fumes.

## 5.3 **Solvent-based acrylic sealants**

These sealants were first introduced to the construction industry in the 1960s. The polymers used are based on alkyl esters of acrylic acid and/or methacrylic acid, with an average molecular weight of less than 80 000. These polymers are usually supplied as 8.5% solution in xylene. A good sealant generally contains 35%–40% polymer. Other ingredients include fillers (40%–45%), solvent (10%–15%), thixotropic agents (2%–3%), catalysts (1%) and plasticisers (1%–5%). Fillers are generally ground calcium carbonates, magnesium silicates and colouring pigments.

Curing occurs by evaporation of solvent. Loss in weight of the sealant occurs owing to solvent evaporation. Therefore, a better sealant is one with lesser weight loss. If the quantity of solvent is greater, weight loss will also be greater. This leads to higher volume shrinkage which in turn may affect the geometry and performance of the sealant (Panek and Cook, 1984).

Solvent-based acrylic sealants are semi-elastomeric because of their thermoplastic nature. The movement accommodation factor is approximately 20%. However, these sealants perform best in the area from  $\pm 7.5\%$

**Table 5.3** Properties of solvent-based acrylic sealants

Property	Typical value or description
Movement accommodation factor	c. 20%
Character	Plastic
Life expectancy	15–20 years
Joint suitability	Perimeter pointing; concrete; stone cladding; precast joints; wood sashes; wood-to-masonry joints
Beneficial properties	Excellent adhesion without the use of primers; minimum surface preparation; one-component system; self-healing; excellent resistance to ultraviolet radiation; good chemical resistance; non-staining
Limiting properties	Poor low-temperature elasticity; poor recovery; strong, offensive odour until it skins; slow skinning and cure rate; unsuitable under water-immersed conditions

to  $\pm 12.5\%$  movement capability. The movement of these sealants is limited because they harden with time as a result of loss of solvent in the system.

Initially, these sealants exhibit a shore A hardness of 25 to 35, which increases slowly with time. A good solvent-based acrylic sealant does not exceed 55 shore A. A higher hardness limits the movement capability and may result in adhesive or cohesive failure of the sealant.

Solvent-borne acrylic sealants have very good weathering properties and exhibit excellent adhesion to a wide variety of substrates without the use of primers. These sealants can even be applied to substrates where slight contamination occurs (Brieton, 1994).

These sealants exhibit some degree of tolerance to contamination from other mastic types and they produce a good durable seal without the need for paint protection. They are well suited for normal outdoor exposures. However, they are not recommended for use in water-immersed conditions as there is a chance of reversion with continuous exposure to water.

Solvent-based acrylic sealants are used for areas where there is limited movement, such as perimeter joints around doors and windows, wood sashes and wood-to-masonry joints, precast joins, panel-to-panel joints and stone cladding. The properties of solvent-based acrylic sealants are summarised in Table 5.3.

## 5.4 Water-based acrylic sealants

Water-based acrylic sealants are also referred to as acrylic emulsion sealants or latex sealants. These are one-component gun-grade material with a solid content ranging from 80%–85%. Curing occurs by evaporation

of water, indicated by formation of surface skin within 30 minutes to one hour at room temperature. Latex sealants have a moderate modulus and low recovery. Most of the sealant suppliers give the movement capability as  $\pm 7.5\%$ . These materials are not suitable for expansion joints. They are basically designed for light construction, which is mostly residential. These sealants are best suited for indoor applications where water is not a factor and movements are minimal in a controlled environment.

Limited outdoor applications are also possible. These sealants withstand rain, but exposure to water will result in loss of adhesion to the substrate.

The average shore A hardness of the cured sealant is 20 to 25 but increases with ageing. Resistance to ultraviolet radiation is excellent, but this is not important for indoor applications. The maximum movement accommodation factor (MAF) can be 15% of the total joint width. Joints should be designed so that movement due to shrinkage and thermal changes does not exceed the maximum MAF, related to the joint width. Table 5.4 lists the properties in general for acrylic emulsion sealants. These properties are summarised from the commercial literature of several acrylic emulsion sealant manufacturers and should not be considered as specifications. Table 5.5 lists the standard specifications for these sealants.

Typical areas of application for water-based acrylic sealants are gaps and joints subject to only a limited amount of movement, for example around door and window frames (Figure 5.1), fixtures and fittings and naturally occurring joints between different building materials. They are

**Table 5.4** Properties of water-based acrylic sealants

Property	Typical value or description
Movement accommodation factor (%)	10%–15%
Life expectancy	10–15 years
Joint suitability	Internal joints; fixtures and fittings; plaster cracks; etc.
Beneficial properties	One-component system; good adhesion without the use of primer; paintable; good resistance to ultraviolet radiation; easy application and clean-up; good packing stability; low cost; fast skinning
Limiting properties	High shrinkage; poor water resistance; limited movement; poor low-temperature flexibility; not recommended for exterior use

**Table 5.5** Standard specifications for water-based acrylic sealants

Country	Standard
Canada	19GP17
USA	ASTM C-834
	US Federal Specification TT-S-00230C

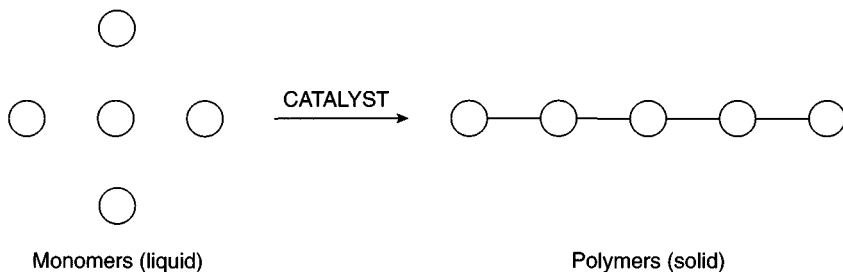


**Figure 5.1** Application of water-based acrylic sealant on window frames

also suitable for use as a joint sealant in brickwork, blockwork and precast construction and in sealing composite and lightweight cladding panels.

### 5.5 Methacrylate-based products

Methacrylates used in the construction industry are low-viscosity, low-odour, high-flash-point liquids which can be chemically converted into tough, solid polymers by the addition of a catalyst (Figure 5.2).



**Figure 5.2** Curing principle of methacrylate systems

Commonly used catalytic processes are as follows:

- peroxide initiation – this involves the use of initiators such as benzoyl peroxide, cumene hydroperoxide etc., under standard atmospheric conditions;
- oxidative cure – cure is initiated in the presence of cobalt salt derivatives such as cobalt neodecanate or cobalt naphthenate;
- thermal activation – depending on atmospheric conditions, at temperatures below 0°C, a bulk curing mechanism can be activated by the addition of amine, for example dimethyl *paratoluidine*.

High molecular weight methacrylate monomers provide advanced technology for polymer concretes and crack sealers. These systems have the advantage of, for example, low odour, low-level toxicity and low shrinkage.

### 5.5.1 *Polymer concretes*

Acrylic polymer concretes make an excellent replacement for traditional concrete for patching and flooring applications. They are generally two-component materials, the first component containing acrylate monomer and the second containing aggregate, which is a blend of sieved sand, pigments and catalyst, which is usually in a powdered form. The two components are thoroughly mixed on-site. Sieve grading of aggregates is important in the desired end-use and strength. Polymer concretes based on methacrylates can be generally prepared by using two basic premix methods: slurry or mortar.

As a slurry, high viscosity resins are combined with graded aggregates, producing self-levelling, low-modulus overlays of 3.2–9.5 mm thickness (ACI, 1993). Where greater thickness and heavier loading capabilities are the principal requirements, mortar systems are used. Mortars are formulated by using low-viscosity monomers to which precisely graded aggregates are added, producing higher moduli than can be obtained with the slurry. Properties of methacrylate binders for polymer concrete overlays are given in Table 5.6.

A primer with low viscosity is applied to the substrate prior to application to ensure a proper bond. Unfilled resin mixed with curing agent

**Table 5.6** Typical properties of methacrylate polymer concrete

Properties	Value	Test method
Pot-life (min)	20–40	–
Cure time (room temperature) (hours)	1–3	–
Bond strength (MPa)	7–14	ASTM C 882
Compressive strength (MPa)	14–62	ASTM C 579
Tensile strength (MPa)	3–8	ASTM D 638
Flexural strength (MPa)	9–21	ASTM C 580



can be used as a primer. The use of methacrylates is restricted to dry surfaces because of their sensitivity to damp and wet conditions.

### 5.5.2 *Acrylate crack injections*

Acrylate crack injections are used to fill cracks and crevices in deteriorated concrete structures. They have a good bonding capacity to concrete and thus provide outstanding structural integrity. Typical applications involve the treatment of concrete cracking caused by the corrosion of reinforcing steel. Acrylate crack-injecting systems offer a simple and effective solution for filling and sealing the cracks, preventing water from entering and providing durable long-term protection (Rohm & Haas, undated).

Water-based acrylic resins offer a suitable means for injection of very fine cracks. The viscosity of such a material is very low which enables a high degree of penetration to be achieved. The resin is suitable for injection of wet cracks in walls, slabs and soffits where the crack widths are less than 0.3 mm (Edwards, 1993a).

## 5.6 **Acrylic coatings**

Concrete is a highly alkaline environment because of the high concentration of calcium oxide or calcium hydroxide. The pH is greater than 12, which protects the steel-reinforcing bars used in the building from corrosion. Carbonation occurs when carbon dioxide reacts with the calcium carbonate and the pH of the environment drops to around 9. In this situation, carbonation becomes rapid, especially in industrialised areas and towns where there is a lot of exhaust emission from traffic. Acrylic coatings have become a versatile choice to overcome the problem of carbonation.

Acrylic coatings have a protective as well as a decorative function. They are marketed in a large range of colours as a single-pack system. These coatings may be applied to atmospherically reinforced concrete structures to protect them from carbonation, chloride ions, oxygens and water. Other than concrete, acrylic coatings can also be applied to protect masonry and other cementitious substrates. Coatings applied to new structures with adequate surface preparation give a long and effective service life. In structures where carbonation has already been initiated, application of acrylic coatings will reduce the rate of deterioration of the concrete. In such cases concrete is coated only after applying a pure filler or levelling coat (Edwards, 1993b).

If conditions are severe, for example if there is widespread spalling and corrosion, patch repairs are carried out, followed by application of acrylic coating as the final part of the repair. Surface treatment with a silane

siloxane-based primer produces a chemically bound hydrophobic barrier, thus inhibiting the passage of water and water-borne contaminants.

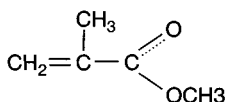
Acrylic coatings allow the free passage of water vapour. In this way water vapour does not build up behind the coating film and cause it to blister. Acrylic coatings for the construction industry are mainly of two types. One is based on methacrylate resins and contains solvent. The other is based on acrylic emulsion copolymer and is totally water-based. This second type is elastomeric in nature and is useful for bridging minor cracks in concrete. Both types prevent carbonation, chloride ingress, and protect from oxygen and water. Elastomeric acrylics are also applied as roof coatings. These types of acrylic coatings will now be discussed individually.

### 5.6.1 Coatings based on methacrylate resins

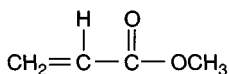
Methacrylate resins are mainly copolymers of *n*-butyl methacrylate, isobutyl methacrylate and methyl methacrylate (Figure 5.3). Methacrylate-based coatings have a number of advantages (Rohm & Haas, 1988):

- UV resistance;
- alkali and acid resistance;
- water vapour permeability;
- carbon dioxide resistance;
- non-yellowing;
- excellent colour retention.

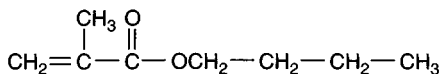
The highly protective effects of methacrylate coatings are achieved at a dry film thickness of about 100  $\mu\text{m}$ . The diffusion resistance to water



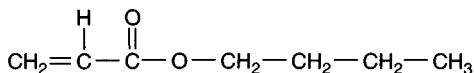
Methyl methacrylate



Methyl acrylate



Butyl methacrylate



Butyl acrylate

**Figure 5.3** Methacrylate resins used for coatings

vapour with such a thickness is generally 1.5 m (corresponding to about 3–4 cm of concrete) and the diffusion resistance to carbon dioxide of about 200 m (corresponding to about 50 cm of concrete). The requirement of an effective carbonisation barrier is thus satisfied by methacrylate coatings. Careful selection of the system and skilful application ensures long-term protection.

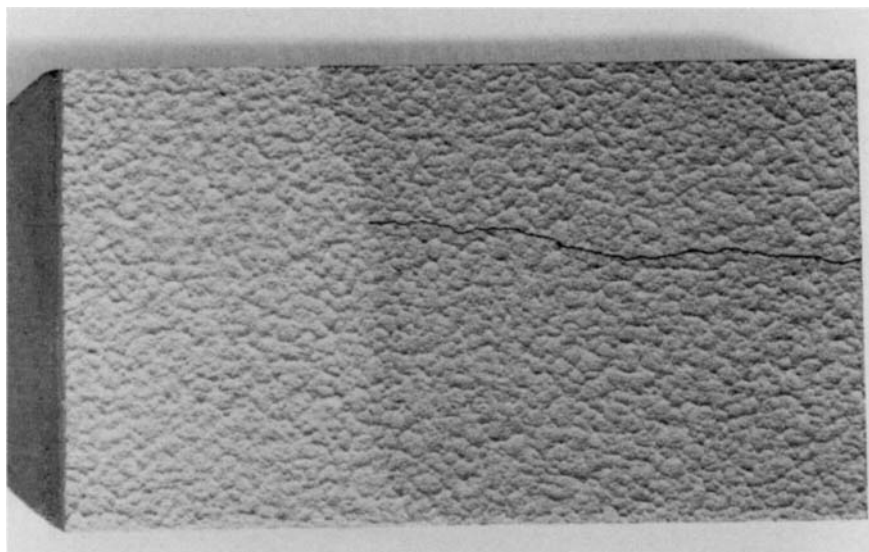
It has been reported (Rohm & Haas, 1988) that the oldest known protected objects with methacrylate-based coating date back to 1960–67 and are still perfectly intact.

### 5.6.2 *Elastomeric coatings for crack bridging*

Crack-injection systems based on epoxy and urethanes are useful for the repair of larger cracks. If small cracks (Figure 5.4) are given such treatment there is a possibility of the development of another crack. Elastomeric acrylic coatings have proved useful for bridging smaller cracks in concrete structures (Figure 5.5). Substrate movement, for whatever reason, leads to cracks, and these cracks can be bridged or protected over the years, through cold winters and hot summers, where the protective coating employs a highly flexible acrylic. This ensures protection of structures from the worst ravages of the weather over a long period of time (Figure 5.6).



**Figure 5.4** Small cracks in a masonry wall



**Figure 5.5** The bridging of small cracks with an elastomeric acrylic coating



**Figure 5.6** A newly constructed residential building protected with elastomeric acrylic coating

Acrylic coatings designed for their crack-bridging capability are based on soft polymers which have a low glass transition temperature (as low as  $-45^{\circ}\text{C}$ ). Such coatings move with cracks in a wall over a wide range of temperatures and prevent ingress of bulk water and penetration by carbon dioxide and chloride ions.

Coating thickness is an important factor for effective crack bridging. Generally, a coating thickness of  $400\text{ }\mu\text{m}$  performs the job satisfactorily. This thickness is achieved in two coats. The thinner the film of conventional coating the less its capability of tolerating the cracks which will appear in the future.

### 5.6.3 *Elastomeric roof coatings*

Elastomeric roof coatings made from acrylic emulsions have an advantage over low-grade asphalts which are prone to deterioration. Roof coatings based on acrylic copolymer emulsions are tough and flexible. Superior resistance is shown to water ponding along with dirt pick-up resistance and reflectivity.

Most acrylic roof coatings have a service temperature of  $60^{\circ}\text{C}$ . Temperatures as low as  $-20^{\circ}\text{C}$  do not alter the coating performance. These coatings provide an effective barrier to carbon dioxide and permeability to water vapour.

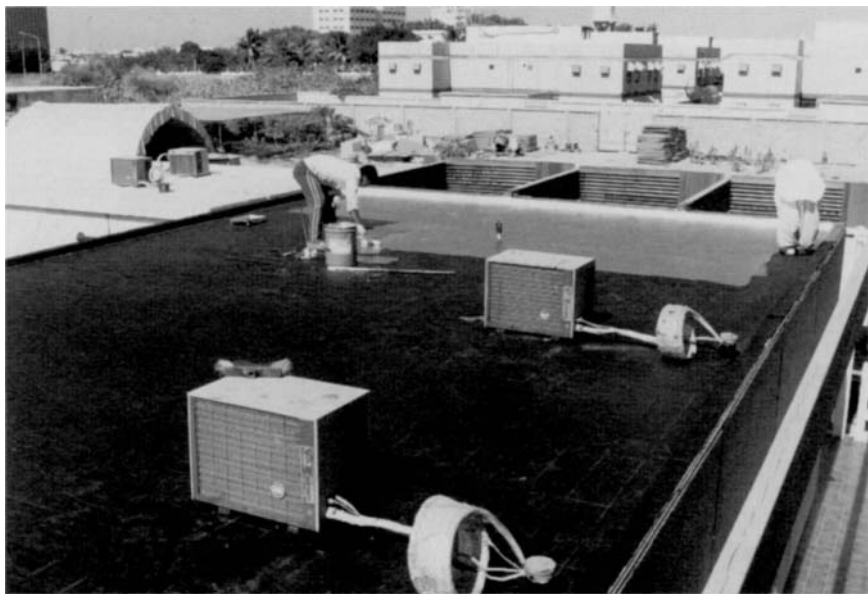
Buildings applied with acrylic roof coatings control the temperature within the building because of their high reflectivity. Thus buildings do not become too hot in summer nor too cold in winter. In this way it is possible to make energy savings in air-conditioned buildings.

Roof coatings can be easily applied by brush, roller or spray (Figure 5.7). The system has low toxicity and odour. Owing to good low-temperature flexibility and high tensile strength the coating can accommodate thermal expansion and contraction of the substrate and generally does not fail over an extended period of time or with extreme weather conditions.

Internally plasticised acrylic systems are more common in today's market. Such systems have greater long-term flexibility which in turn provides durability to the coating.

## 5.7 **Acrylics as cement modifiers**

There are many deficiencies associated with unmodified cement mortars, such as the potential for incomplete hydration (especially in thin sections), poor adhesion and the high water level needed for adequate workability. Above all, cement is a brittle product with low flexural strength, impact resistance and abrasion resistance (Rohm & Haas, 1989).



**Figure 5.7** Application of acrylic roof coating. Reproduced with permission from Fosroc

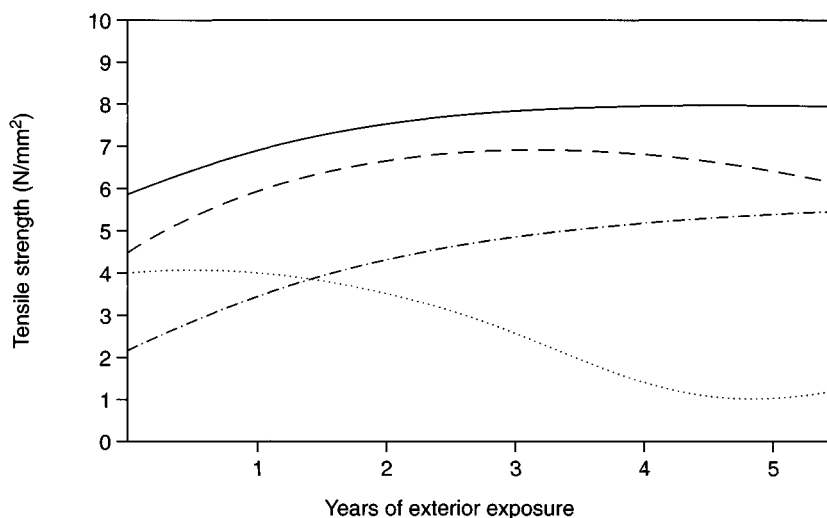
As a result of technological breakthroughs, an array of polymers has been used as cement modifiers which provide stronger and more durable compositions, excellent adhesion and good thin-section applications. Commonly used polymers for cement modification include styrene-butadiene, liquid latex, vinyl acetate emulsion, vinyl acetate-ethylene copolymer redispersible powder, acrylic copolymer emulsion, acrylic powders and so on. Among the several cement modifiers, acrylic polymers are found to be fully effective. They offer many significant properties, such as:

- excellent bond strength to a wide variety of substrates, including concrete masonry, bricks, glass, metal and wood;
- superior tensile strength, flexural strength and impact strength;
- excellent abrasion resistance;
- excellent water resistance (hydrophobic);
- superior freeze-thaw resistance;
- UV resistance;
- low water/cement ratio requirement;
- superior handling and application properties;
- excellent workability and a selected balance between open time and set time.

Figure 5.8, which is the result of extensive research by Rohm & Haas (1991), illustrates the comparative durability of polymer-modified cements. A comparative study carried out by Rohm & Haas (1989) of different cement modifiers concluded with the following results:

- styrene-butadiene rubbers (SBRs) severely discolour on exposure to sunlight;
- polyvinyl acetates (PVAs) undergo hydrolysis of the polymer in moist, alkaline conditions such as wet cement; on long exposure, PVA-modified samples were found to be worse than samples with no modifier;
- acrylic polymers provide exceptional durability because of their superior resistance to UV radiation. They do not yellow or chalk under these conditions and they do not hydrolyse readily and thus hold up well in wet environments (Rohm & Haas, 1991).

When acrylic polymers are added into a cement mortar mix, their spheres coalesce to form a continuous polymer matrix which coats the hydrating cement grains and aggregate. This polymer matrix acts as a barrier which helps to improve the hydration of the cement and also provides a polymeric network which increases the toughness and durability of the finished product.



**Figure 5.8** The comparative durability of polymer-modified cements. - · - · - = unmodified cement; — = acrylic-modified cement; - - - = styrene-butadiene-rubber-modified cement; . . . = polyvinyl-acetate-modified cement. Source: Rohm & Haas, *Which Cement Modifier Modifies Best?*, Philadelphia, PA, 1991

Acrylic latices have been used successfully for more than 35 years to modify portland cement composites. The use of solid grade acrylic cement modifiers has become common during the past few years. Both of these types will be discussed later in this section. The level of polymer modification is measured as a ratio of polymer solids by weight of cement. A 15%–20% modification represents the range for optimum performance; lower modification levels may prove acceptable for certain product applications (Rohm & Haas, 1989).

In polymer-modified cement systems, there occurs air entrapment resulting from the generation of foam while mixing. Air has an adverse effect on the mechanical strength properties of cement mortars as expressed by Feret's relationship:

$$\text{relative mechanical strength} = k_0 \left[ 1 + \frac{D_c (w + a)}{c (1 + k_1 + k_2)} \right]^2$$

where

$k$  is constant and is a function of the cement type;

$k_1$  is the pozzolanic activity coefficient;

$k_2$  is the filler activity coefficient;

$w$  is the water content;

$a$  is the air content;

$c$  is the cement content;

$D_c$  is the cement specific gravity.

By using a suitable defoamer one can maintain the density very close to that of an unmodified mortar. In most cases, the wet density of the mix should be 2 g/cm<sup>3</sup> or higher.

Polymer-modified cement systems are composed of sand, portland cement, polymer and a defoamer. Products modified with acrylic emulsions are two-component systems with sand and cement as one component and modifier emulsion and liquid defoamer as the second. Those modified with powdered polymers are one-package systems. In this case, dry defoamer is used. Water is added in both types of system for workability. Selection of aggregate type and particle size is very important for density, texture, chemical resistance, levelling characteristics and workability. Very fine aggregates such as silica flour or marble dust will have a higher water and cement requirement because of the higher surface area/volume ratio (Rohm & Haas, 1989). Aggregates should be prewashed and dried to reduce the content of inorganic salts, which contribute to the development of efflorescence.

When applying the cement the following considerations should be taken into account.

- The application temperature must be maintained above the minimum film forming temperature until the completion of the film formation



process, which generally ranges between 10°C (50°F) to 12°C (54°F). Room temperature (20°C–25°C) (68°F–77°F) and 50% to 60% relative humidity are considered to be ideal.

- Modified systems generally have a pot-life of 1–2 hours under ambient temperature and humidity. In the case of higher temperatures, the pot-life will decrease. Therefore, additives can be used to improve open time and workability.
- In the case of unsound substrates, loose and disintegrated material, oil, grease and other chemicals should be removed with a detergent followed by thorough washing with water. Owing to the excellent adhesion of acrylic-modified mortars, etching or roughening of the surface is not needed.
- Overtrowelling should be avoided as this may result in polymer floating to the surface or in tearing of the surface.
- Spray coats should be applied by using a fluid horizontal movement to maintain the spray head at an even distance.
- Unlike unmodified mortars, which require laborious moist curing conditions for optimum strength properties, polymer-modified mortars should be air-cured at ambient temperature and relative humidity.

### 5.7.1 *Acrylic emulsions*

Acrylic emulsions (or acrylic latices) are characterised as high-solids polymers having a film-forming temperature at or below room temperature (Lavelle, 1986). They have excellent hydrolysis resistance compared with other resins and are well suited as modifiers for portland cement mortars. Studies have shown that certain acrylic latices impart excellent workability at lower water demand, thin section adhesion and toughness, improved flexural strength and tensile strength and outstanding adhesion (Lavelle, 1983).

Individual acrylic latices from various manufacturers may have more or less the same properties. Table 5.7 lists the physical properties of some commercial latices used for cement modification.

Commercial grades are designed for specific end-uses, for example there are separate grades for trowel-applied products and for sprayable products. Cement systems modified with acrylic emulsion are used in numerous applications, as listed below:

- patching repair mortars;
- floor underlays and overlays;
- terrazzo floorings;
- ceramic tile adhesives;
- precast architectural building panels;
- stuccos;

**Table 5.7** Physical properties of commercial acrylic emulsions used as cement modifiers

Property	Typical value or description
Appearance	White, milky liquid
Solids content	47% $\pm$ 1%
Specific gravity	1.05 $\pm$ 0.01
pH	9.5–10
Minimum film-forming temperature	10°C–12°C
Freeze–thaw stability	Five cycles

- grouts;
- cementitious coatings;
- renders and shotcretes;
- highway and bridge deck repair products.

### 5.7.2 Modifiers based on solid acrylics

These are redispersible powders of 100% acrylic composition and are readily redispersible in water. They are manufactured by spray drying of the appropriate latex. Addition of some inorganic fillers prevents the caking of these powders.

In recent years solid grade acrylic cement modifiers have become more popular, for many reasons:

- they are one-package systems;
- they show fast redispersion;
- they have a low-film forming temperature;
- they are easy to store;
- they have a low foam-formation tendency;
- they have excellent thin-section toughness and adhesion;
- they show low water demand;
- they exhibit durability and colour retention.

The physical properties of acrylic redispersible powders are given in Table 5.8. Tsai *et al.* (1993) have reported that the particle size distribution of

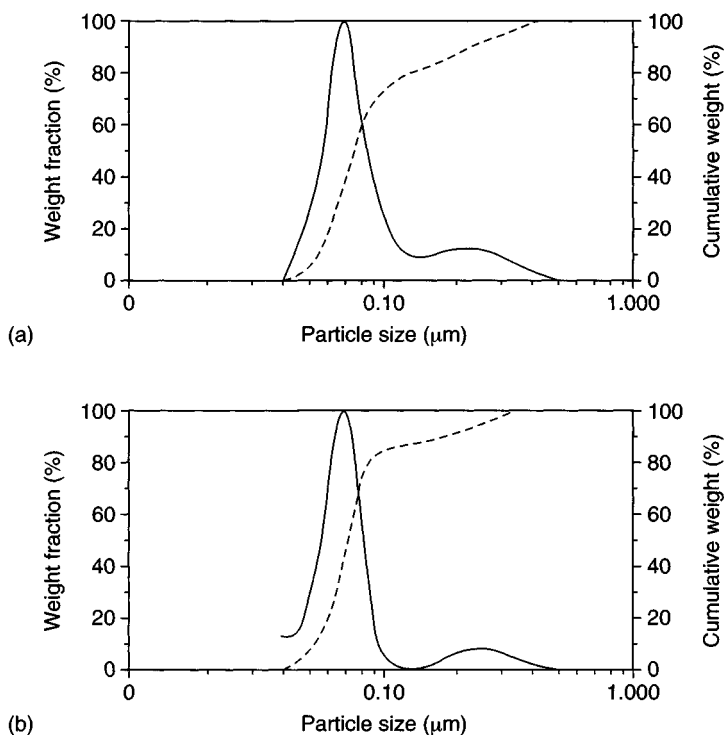
**Table 5.8** Typical physical properties of acrylic redispersible powders. Source: Tsai, M.C., Burch, M.J. and Lavelle, J.A., Solid grade acrylic cement modifiers, in *Polymer Modified Hydraulic Cement Mixtures*, ASTM STP 1176 (eds L.A. Kuhlman and D.G. Walter), Table 1; published by the American Society for Testing and Materials, Philadelphia, PA, 1993

Property	Typical value or description
Appearance	White, free-flowing powder
Moisture content	< 2.5%
Particle size	Maximum 5% on 20-mesh screen
Ash content	< 5%
pH of redispersion (30% solids)	8–12

redispersion was essentially the same as that of its parent latex. The reversibility of particle size distribution indicated that parent latex properties have been preserved during spray drying isolation (Figure 5.9). It was also noted that mortar modified with redispersible acrylic powder is similar in performance to that of a commercial acrylic latex (Table 5.9).

Application areas for powdered acrylics as cement modifiers are as follows:

- self-levelling cementitious floors;
- corrosion-resistant metal primers;
- concrete repair and patching mortars;
- ceramic tile thinsets and grouts;
- shotcrete;



**Figure 5.9** Particle size distribution of (a) an acrylic powder redispersion; (b) the original latex. Solid concentration = 1%. — = weight fraction (percentage of maximum); - - - = cumulative weight (percentage of total). Reproduced with permission from Tsai, M.C., Burch, M.J. and Lavelle, J.A., Solid grade acrylic cement modifiers, in *Polymer Modified Hydraulic Cement Mixtures*, ASTM STP 1176 (eds L.A. Kuhlman and D.G. Walter), Figure 1; published by the American Society for Testing and Materials, Philadelphia, PA, 1993

**Table 5.9** Properties of acrylic-modified mortars compared with unmodified mortars. Source: Tsai, M.C., Burch, M.J. and Lavelle, J.A., Solid grade acrylic cement modifiers, in *Polymer Modified Hydraulic Cement Mixtures*, ASTM STP 1176 (eds L.A. Kuhlman and D.G. Walter), Table 2; published by the American Society for Testing and Materials, Philadelphia, PA, 1993

Polymer modifier	Acrylic powder A	Acrylic latex	Unmodified mortar <sup>a</sup>
Water/cement ratio	0.46	0.43	0.55
Thin-section toughness	Very good	Very good	Poor
<i>Compressive strength</i> (ASTM C 109) (MPa):			
1 day at RT	14.5	14.5	14.5
28 days at RT	31.0	25.5	25.5
<i>Shearbond adhesion</i> (MPa)			
14 days at RT	3.7 (C)	3.8 (C)	0.8 (A)
7 days at RT and 7 days in water	2.6 (C)	1.9 (C)	1.6 (A)
<i>Tensile strength</i> (ASTM C 190) (MPa):			
7 days at RT	3.7	4.1	2.6
7 days at RT and 7 days in water	3.4	3.2	2.2
<i>Flexural strength</i> (ASTM C 348) (MPa):			
7 days at RT	7.6	5.5	5.5
28 days at RT	13.1	10.3	5.5

<sup>a</sup> Unlike polymer-modified mortars, unmodified mortars require moist cure for optimal effect. ASTM codes. C = cohesive failure; A = adhesive failure.

Note: RT = room temperature.

- renders;
- dry powder paints and textured coatings.

The formulation of cementitious products with use of powdered acrylics is accomplished through dry blending. After gaining information on cement-modifying acrylics, let us now gain an idea of two broad spectrums of such acrylics: acrylic-cement repair mortars and acrylic-cement protective coatings. These discussions are equally applicable to acrylic emulsions as well as to powdered acrylics.

**5.7.2.1 Acrylic-cement mortars.** The term 'mortar' as used here includes concrete repair and patching mortars, grouts, adhesives and floorings. They have good resistance to permeation by chlorides. In the form of flooring, they offer water-resistant and high-strength floors which are generally trowel-applied. They offer good adhesion as tile adhesives and grouts.

As a concrete repair and as patching mortars they are used to:

- repair damaged, decayed, weak or debonded concrete;
- replace spalled, chipped or cracked concrete;

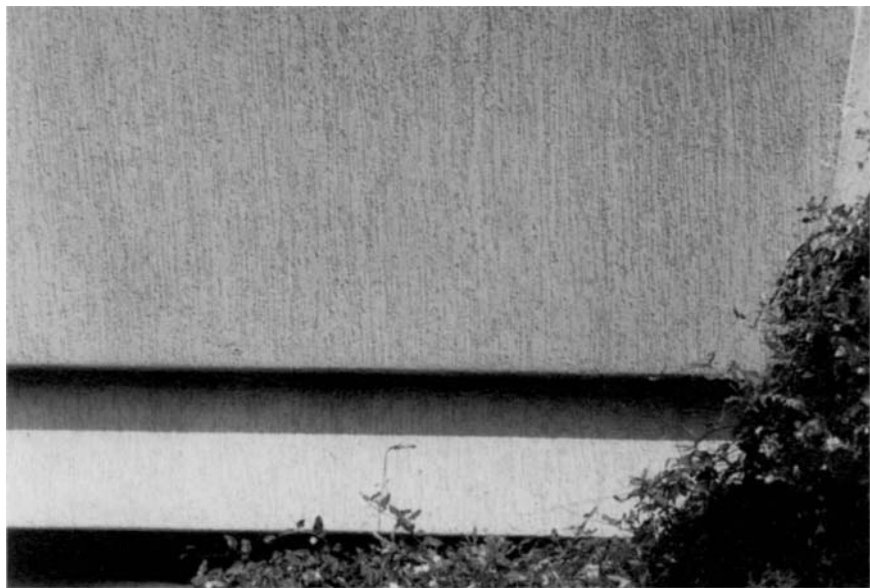
- replace concrete suffering from carbonation or chloride ion ingress;
- fill honeycombs in new or old constructions;
- reprofile concrete or masonry.

Repairs can be made in vertical and overhead situations.

It is important that acrylic-modified cement mortars be marketed based on their end-use; for example mortars for concrete repair and for use as ceramic tile adhesives are sold as separate products. Therefore, one should not become confused that a single mortar is used for all of the above-mentioned functions.

*5.7.2.2 Acrylic-cement protective and decorative coatings.* Coatings based on acrylic latex are available as two-pack systems. Those based on powdered acrylic polymer have captured the market. These coatings have a protective as well as a decorative function (Figure 5.10). They have excellent colour stability and durability. Lavelle (1986) reported that acrylic-latex-modified white cement coating was found to show excellent colour retention and durability even after 11 years of exterior exposure. Coating based on white cement can be pigmented to give the desired colour.

Acrylic-modified cement coatings protect atmospherically exposed reinforced concrete structures from attack by chloride ions, oxygen and water.



**Figure 5.10** Acrylic-cement coating applied on a building to perform a protective as well as a decorative function

It is also possible to reface and even take out variations in concrete and masonry surfaces and bridge shrinkage cracks. Such coatings find application on walls, buildings, roofs, water tanks, reservoirs and so on.

The coating can be applied by brush, roller or spray on contamination-free and prepared substrates (Figure 5.11). Some advantages of acrylic cement coatings are as follows:

- they provide a barrier to chloride ions, carbon dioxide, oxygen and water;
- they are permeable to water vapour;
- they are non-toxic;
- they are resistant to the effects of long-term weathering and are durable in all climatic conditions;
- they are resistant to UV radiation.

An increased polymer level may improve the water resistance of such coatings. Some manufacturers market special grades, claiming their suitability for moist areas, especially in coastal environments.

## **5.8 Acrylic latex as an asphalt modifier**

In order to modify asphalt, 100% acrylic latex is used. Special latices are marketed for this purpose. The latex can be post-added to asphalt emulsion followed by agitation to prevent stratification.

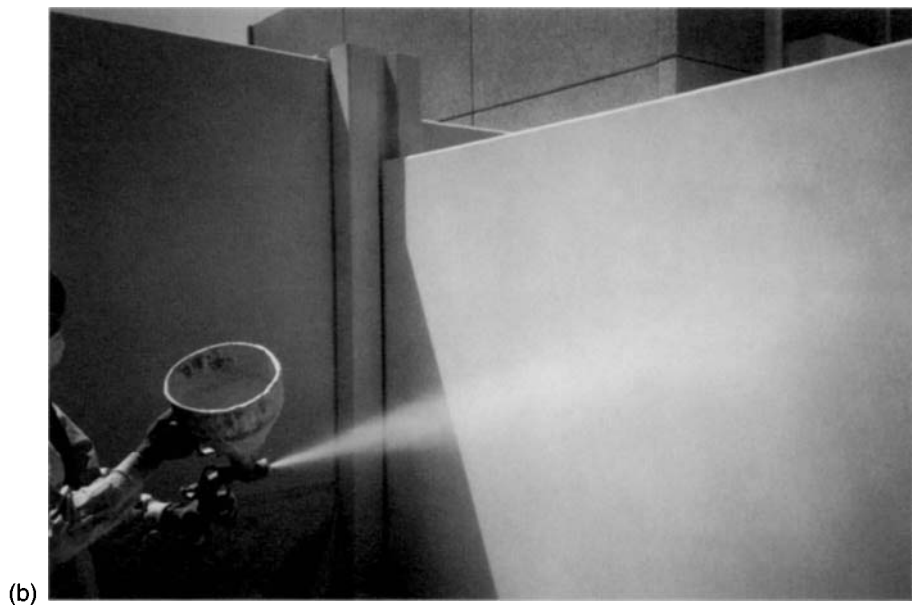
The addition of 100% acrylic polymers enhances the following properties of asphalt film (Rohm & Haas, 1990):

- weatherability;
- resistance to surface cracking, chalking and UV degradation;
- resiliency;
- added tensile strength and elastomeric recovery;
- flexibility;
- improved low-temperature toughness;
- oil and gas resistance.

Generally, modification is made by adding approximately a 15% level of acrylic latex. Modified asphalt displays improved properties. Acrylic-modified asphalts are used for parking lots, driveways, low-volume off-highway streets and highway shoulders.

## **5.9 Acrylic construction adhesives**

These adhesives are based on an acrylic copolymer emulsion. They have a wide range of applications and are classified accordingly as:



**Figure 5.11** Application of an acrylic-cement coating: (a) by brush; (b) by spray-gun.  
Reproduced with permission from Fosroc

- flooring adhesives – these are used for a variety of floor covers such as polyvinyl chloride (PVC) linoleum, carpet and rubber and have outstanding hold-down properties on all substrates such as concrete, wood, tiles and so on;
- contact adhesives – these are used to contact two similar or dissimilar substrates and have good adhesion characteristics;
- panel adhesives – these provide adhesion to wood, plaster, aluminium, tiles and so on and they have outstanding early and late grab, with good shear and bond strength;
- tile adhesives – these are used to fix tiles on walls; such adhesives have good rheology to prevent sagging (Figure 5.12).

### 5.10 Acrylic floor-care polymers

Floor-care polymers are based on pure acrylics or styrene acrylics, cross-linked with metals (e.g. zinc). Floor polishes formulated with acrylics have a number of advantages, as listed below:

- good water resistance;
- resistance to block and heel marking, scuffing and dirt pick-up;
- slip resistance;
- spray buffability;



**Figure 5.12** Tiles fixed with acrylic adhesive, which offers excellent adhesion



- powdering resistance;
- high gloss;
- good removability.

Some products can be used in industrial applications as interior concrete sealants.

### 5.11 Health and safety

No hazards are associated with acrylic polymers in their raw form or their finished state. A few hazards are associated with some compounding ingredients which need proper care during handling, storage and application.

Peroxides, which are used as curing agents for methacrylates, are oxidative in nature. These should not be subjected to high temperatures, fire or acids. Certain biocides used in acrylic formulations are toxic in nature. Such products should not be allowed to make contact with skin or eyes. In the event of such contact, thorough washing should be made with clean water.

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## **6 Silicones in the construction industry**

### **6.1 Introduction**

Today, silicones have become virtually irreplaceable materials worldwide and have an extremely wide range of applications. The use of silicone room-temperature vulcanising (RTV) elastomers in the construction industry originated in the early 1960s. The value of silicone RTV elastomers is based on important properties such as their thermal stability, unusual surface properties, water repellency, high permeability, oxidative stability and ultraviolet (UV) resistance (Cash, 1970).

Silicones offer three major technologies to the construction industry in the form of sealants, water repellents and coatings. These technologies are not new to advanced countries but have become common in developing countries only over the last few years. This is probably a result of the steady growing awareness of these technologies in Third World countries. In the form of water repellents silicones are performing an important job in the protection of masonry. All structural glazing practices are utilising silicone sealants with success. Silicone sealants are thus considered as successors to polysulphide sealants in the field of structural glazing.

Silicone coatings are used for specific applications where low-temperature flexibility, water repellency and the bridging of small cracks is desired. Protection of monuments is also carried out with silicone coatings. Table 6.1 highlights the specific properties and application areas of silicone systems in the construction industry. In light of environmental regulations new technologies are being introduced and further research for more friendly materials is in progress by manufacturers as well as research institutions.

### **6.2 Properties**

#### *6.2.1 Silicones compared with carbon compounds*

The differences between silicon and carbon chemistry are given in Table 6.2. Typical properties are given in Table 6.3.

**Table 6.1** Specific properties and applications of silicone systems in the construction industry

Product and properties	Application areas
Sealants: durability resistance to heat; cold water, ozone and ultraviolet radiation adhesion to a variety of substrates high recovery colour stability	glazing sealants construction sealants (neutral cure systems) sanitary sealants
Water repellents: water repellency permeability to vapour frost resistance durability	masonry structures natural stones protection of concrete
Coatings: permanent flexibility ability to bridge small cracks resistance to weathering, ageing, radiation, ozone and temperature	protection of monuments as a weather-resistant coating for building materials rust and corrosion resistance coating on metallic rooves and tank surfaces, etc.

**Table 6.2** A comparison of silicon with carbon chemistry

Property	Silicon	Carbon
Electropositivity	More electropositive	Less electropositive
Bond energy $E$ (kcal/mol)	$E(\text{Si—O}) = 105\text{--}108$	$E(\text{C—O}) = 85\text{--}91$ $E(\text{C—C}) = 83\text{--}85$
Bond type	Bond has ionic character	Covalent bonds are common
Electron density	Low	High

### 6.2.2 General properties

Silicones have greater chain flexibility than carbon-carbon bonded polymers, and the resulting long-chain siloxanes have a low glass transition temperature, at around  $-120^\circ\text{C}$ .

Because of their low intermolecular cohesion, silicone polymers generally have low mechanical strength. At the same time, the low intermolecular cohesion is associated with excellent gas permeability and low surface energy (Kyokaishi, 1993).

A strong binding affinity to electronegative entities predicates strong thermal resistance and weatherability.

### 6.2.3 Heat resistance

Silicones perform well at temperatures higher than  $150^\circ\text{C}$ . Temperatures of up to about  $300^\circ\text{C}$  can even be withstood for a short time without substantial changes to physical properties (Noll, 1968).

**Table 6.3** Typical properties of silicone elastomers

Property	Typical values or description
General chemical structure	$  \begin{array}{c}  \text{R} \qquad \text{R} \\    \qquad   \\  \text{---Si---O---Si---} \\    \qquad   \\  \text{R---CH}_3, \quad \text{C}_2\text{H}_5  \end{array}  $
Hardness range (shore A)	10–85
Glass transition temperature (°C)	–60
Service temperature (°C)	–90 to 250
Heat resistance	Excellent
Cold resistance	Excellent
Tensile strength	Low
Tear strength	Poor
Resilience	Excellent
Elasticity	Moderate
Flame resistance	Excellent
Ageing resistance (general)	Excellent
Sunlight resistance	Excellent
Ozone and corrosion resistance	Excellent
Electrical resistivity	Moderate
Optimum properties	Maximum heat and cold resistance
Limiting properties	Low strength

#### 6.2.4 Adhesion

Silicone products give excellent adhesion to many substrates used in the building industry (e.g. concrete, glass, ceramics and metals), and in most cases primers are not needed. However, the use of primers gives much stronger adhesion.

#### 6.2.5 Surface properties

Silicones exhibit excellent water repellency. This property has provided the unplanned benefit of protecting mineral building structures and monuments.

#### 6.2.6 Water absorption and permeability

As compared with their low water absorption, silicone elastomers show an extremely high rate of water vapour transmission. The positive aspect of this property permits one to apply silicone systems over concrete masonry and other substrates upon which other polymeric coatings blister, crack and peel (Cash, 1970). The negative aspect is that silicone rubber cannot be used as a vapour barrier. The permeability to liquids is less compared with that to vapours.

### 6.2.7 *Resistance to ozone and ultraviolet radiation*

Silicone rubbers are highly resistant to the action of oxygen and ozone on natural ageing. They also have resistance to the action of intense UV radiation. Silicone rubber may be regarded as one of the most weather-resistant elastomers, even though there is some decrease in the mechanical properties on storage in open air for several years (Noll, 1968).

### 6.2.8 *Mechanical properties*

The mechanical properties are as follows:

- room-temperature vulcanisates have poorer mechanical properties than do heat vulcanisates;
- good elastic properties are obtained with suitable formulations;
- the strength of silicone rubbers is generally inferior;
- silicones have smaller abrasion resistance compared with other types of rubber.

### 6.2.9 *Low-temperature flexibility*

Silicone rubbers are flexible even at low temperatures. The stiffening temperature ranges from 50°C to 70°C, depending on the formulation.

### 6.2.10 *Chemical resistance*

Silicones are resistant to water between 0°C and 100°C. Steam, at higher temperatures in prolonged attack, destroys the system. Normally, silicone rubbers are resistant to salt solution and to dilute solutions of acids and bases. However, they are not resistant to organic solvents. In this case a reversible swelling takes place.

## 6.3 **Silicone sealants**

Silicone sealants have been used in the construction industry since the early 1960s. In today's world they are finding a wide range of applications in several areas of construction. They are considered as durable among the range of sealants available to the construction industry. The most common type of building sealants are generally based on a one-component system which cures rapidly on exposure to the atmosphere. Two-component silicone sealants are also available and are used in areas where a high application thickness is required. However, their use is very limited.

Although in this section one-component and two-component sealants are going to be discussed, the text is inclined towards one-component

**Table 6.4** Properties of one-component and two-component silicone sealants

Property	One-component	Two-component
Movement ability (percentage of joint)	$\pm 25$ to $\pm 70$	$\pm 25$ to $\pm 50$
Service temperature ( $^{\circ}\text{C}$ )	-50 to 150	-50 to 150
Initial curing time (hours)	1-3	c. 2
Complete cure time (days)	7-21	3-7
Shrinkage (%)	0-5	0-5
Hardness (Shore A)	15-40	15-40
Chemical resistance	Both are unaffected by industrial wastes, gases, water, alcohol, dilute acids and alkalis, soap and household detergents.	

sealants because of their extensive use. Important properties of one-component and two-component silicone sealants are summarised in Table 6.4

The properties that make silicone sealants a versatile choice are:

- superior durability;
- resistance to heat, cold, water, ozone and UV radiation;
- excellent adhesion to a variety of substrates, such as glass, metal, concrete, natural stone, various plastics, etc.;
- good colour stability;
- high recovery, as much as 98%;
- no surface cracking or chalking on exposure to UV light;
- good compression set resistance;
- no shrinkage occurs during the cure;
- exceptionally stable viscosity.

Temperature has little effect on the gunning characteristics of the sealant. They can be applied in the temperature range  $-50^{\circ}\text{C}$  to  $150^{\circ}\text{C}$  (Wacker-Chemie, 1988).

### 6.3.1 One-component silicone sealants

As already mentioned, one-component silicone sealants cure by moisture pick-up from the atmosphere to form permanently elastic rubber. There are different types of curing systems for one-part silicone sealants (Table 6.5). However, the most commonly available systems are the acetoxy and neutral curing systems.

In acetoxy systems acetic acid is produced during cure. This type of system is not ideal for use on alkaline surfaces. However, it has excellent adhesion to glass and glazed ceramics, making it ideal for use in all types of glazing and sanitary applications. Acetic system types should not be used on sensitive surfaces (e.g. concrete, zinc, lead, copper, brass, iron and some coated glasses).

**Table 6.5** Curing systems for one-part silicone sealants

Type	pH rating
Acetoxy	Acid
Octoyloxy	Acid
Amine	Alkaline
Oxime	Alkaline
Aminoxy	Alkaline
Alcoxy	Neutral
Amide	Slightly alkaline

In amine systems ammonia is released during the cure. This system can be used with alkaline materials. The cured sealant possesses the lowest modulus of all such systems.

The neutral cure system does not release any acid by-products during cure and therefore this type can also be used for alkaline substrates.

The influence of the cross-linking system on silicone sealants is shown in Figure 6.1

The disadvantages of one-component silicone sealants include:

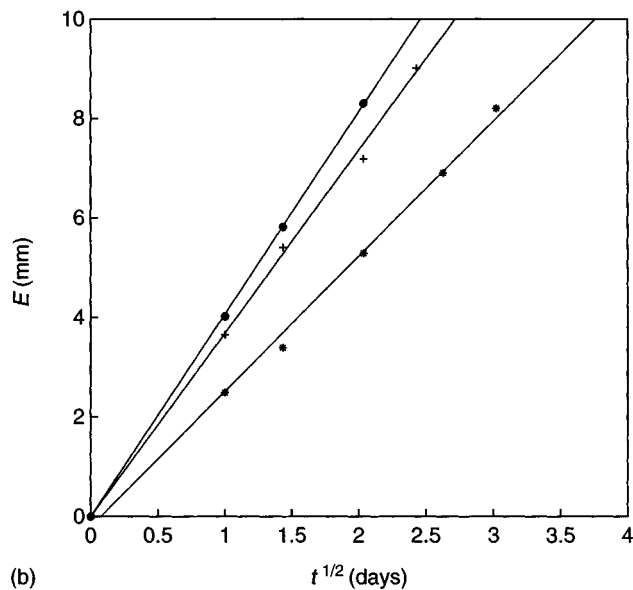
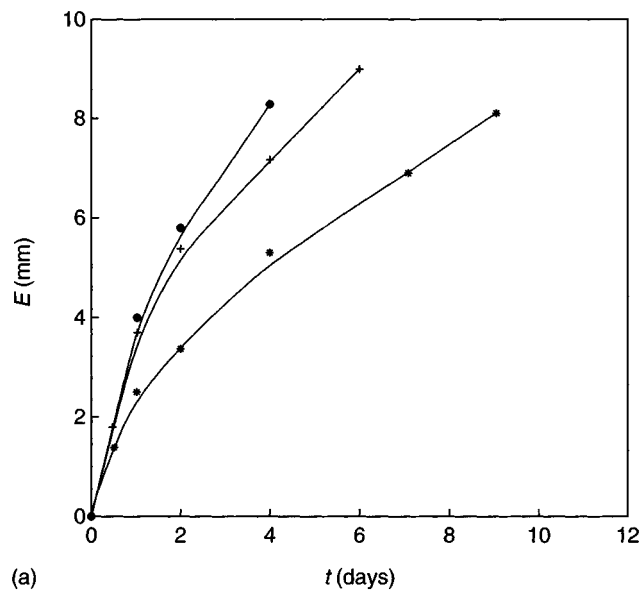
- surface preparation is critical;
- dirt pick-up;
- the short tooling time owing to fast skinning;
- an unpleasant odour for acetic systems;
- non-paintability;
- surface staining in the case of overplasticised formulations;
- acetic cure systems are not compatible with zinc, lead, brass, iron, coated glasses and concrete.

One-component silicone sealants are commercially supplied in 310 ml plastic cartridges which can be opened and readily applied with the aid of an application gun.

The main areas of application for one-component silicone sealants are glazing, structural glazing, construction, sanitary areas and as insulated-glass sealants. All these topics will be covered in the section on specific areas of application (section 6.3.8).

### 6.3.2 Two-component silicone sealants

These sealants are available in two packs, one containing polymer (known as the base) and one containing catalyst or curing agent. Both the components are mixed thoroughly on site for 10–15 minutes prior to application. Their use is not very common. They are used in situations where there is a large joint in places where fast and thorough cure is desired. Application areas include the field of civil engineering as well as structural glazing.



**Figure 6.1** The influence of the cross-linking system in silicone sealants: (a) cured thickness,  $E$ , against cross-linking time,  $t$ ; (b) cured thickness,  $E$ , against the square root of cross-linking time,  $t^{1/2}$ , to illustrate the diffusion law

$$E = Kt^{1/2}$$

for acetoxysilane,  $K = 4.15 \text{ mm/s}^{1/2}$ ; for oxime sealant,  $K = 3.70 \text{ mm/s}^{1/2}$ ; for the alkoxy sealant,  $K = 2.75 \text{ mm/s}^{1/2}$ . ● = acetoxysilane; + = oxime sealant; \* = alkoxy sealant. Reproduced with permission from Rhône-Poulenc Silicones, Lyon, France



The disadvantages of two-component systems are that:

- the two components require thorough mixing;
- an application gun is needed for filling;
- equipment cleaning is essential after application.

### 6.3.3 Compounding

Both one-component and two-component silicone sealants contain polydimethyl siloxane as the base polymer along with fillers such as calcium carbonate and/or fumed silica fillers, plasticisers (silicone oil) and a variety of cross-linking agents and adhesion promoters. Two-component sealants utilise a catalyst such as dibutyl tin dilaurate, alkyl silicate esters and metallic salts (Maslow, 1982).

Two-component materials often use water as the chemical curing agent, by using wet fillers or by adding water to one of the components (SWRI, 1995). A fungicide can be incorporated in sealants used for moist environments (i.e. sanitary sealants).

### 6.3.4 Modulus

Silicone sealants can be formulated to have a low modulus as well as a high modulus. Some manufacturers also supply an intermediate class described as mid-modulus. The choice of reactive silicone oils with different viscosities allows one to obtain sealants with variable elastic moduli.

Low-modulus sealants are usually preferred when the joint elongation is high (over 25% of joint width) whereas high-modulus sealants are chosen for assembly where the elastic movement under strain is reduced to a minimum (Houde, 1993). Table 6.6 gives the properties and applications of silicone sealants depending upon their modulus.

A proper reactive polymer cross-linking system combination allows the accomplishment of a range of products which can meet various building applications.

**Table 6.6** Properties of silicone sealants, depending upon modulus

Modulus	MAF <sup>a</sup>	Character	Life expectancy (years)	Application area
Low	50–70	Elastic	25–30	Building expansion joints, curtain walling, etc.
High	20–30	Elastic and elastoplastic	25–30	Structural glazing joints, aquarium joints, sanitary ware

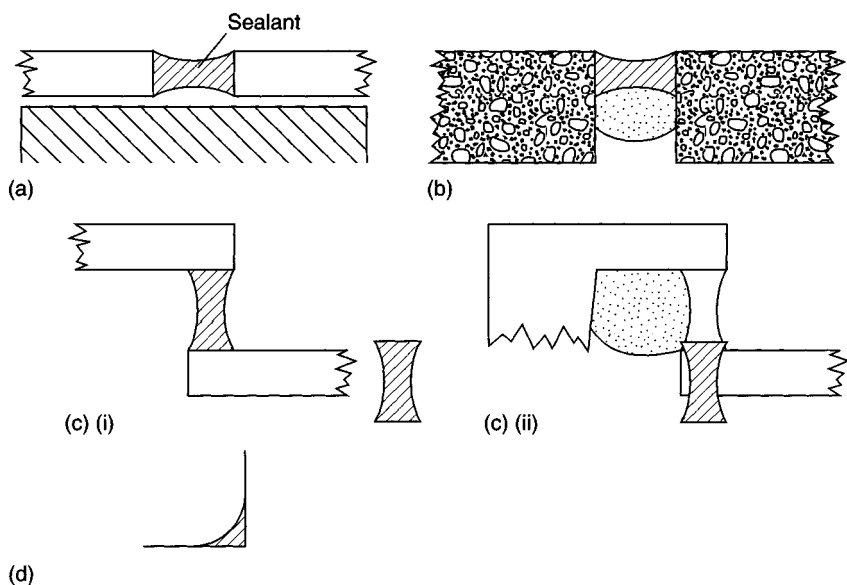
<sup>a</sup> Movement accommodation factor.

### 6.3.5 Types of joints and suitable products

Different types of joints are associated with silicone sealants. The curing system and modulus of a sealant are important factors for the joint application type. Figure 6.2 illustrates the type of joints and Table 6.7 lists suitable products for use with each type of joint.

The following points are considered in a proper joint design procedure.

- A low-modulus sealant is recommended if the thermal expansion or contraction is likely to be greater than 25%.
- The depth of sealant should be half the width of the joint.
- A minimum width and depth of 5 mm are necessary for joints in glass. For metal and concrete joints in which movement is foreseen, a minimum width and depth of 10 mm is required.
- To adjust the depth of the sealant joints and to prevent the sealant from bonding to the bottoms of the joints a backing material, made of polyethylene, is used as a bond breaker [Figure 6.2(c)].
- In concrete and stone joints, the bonding area can be increased by using circular backing material.
- A depth:width ratio of between 1:1 and 1:5 is generally appropriate. The minimum and maximum dimensions for the sealant joint are given in Table 6.8.



**Figure 6.2** Joint types: (a) butt joint; (b) expansion joint; (c) (i) glass-to-glass lap joint, (ii) concrete-to-concrete lap joint; (d) triangular joint (e.g. sanitary seals and glazing seals).  
 ▨ = sealant; ▤ = backing material [part (c)]

**Table 6.7** Suitable sealants for use with various joint types (as illustrated in Figure 6.2)

Joint type	Silicone sealant
Butt joint	High-modulus or mid-modulus, acetic-cured or neutral cured sealant
Expansion joint	Low-modulus neutral cure sealant, to accommodate the movement in the joint
Lap joint:	
glass-to-glass	Mid-modulus or high-modulus, neutral cure sealant
concrete-to-concrete	Low-modulus, neutral cure sealant
Triangular joint	High-modulus or mid-modulus, acetic-cured or neutral cure sealant

**Table 6.8** Minimum and maximum dimensions for sealant joints

Use	Minimum (mm)		Maximum (mm)	
	Width	Depth	Width	Depth
Glazing	5	5	30	20
Other	10	10	40	20

### 6.3.6 Primers

Although silicone sealants adhere to many unprimed substrates, primers may be required to achieve long-term adhesion to some substrates. Primers may also be required to minimise the risk of migratory staining from the sealant into the adjacent substrate.

The use of primers is also advisable if the bonded parts are to be subjected to temperature changes, damp conditions, tension compression, shear forces, etc. Some porous substrates and plastic materials also require primers. Primers can be applied to a thoroughly prepared surface by brushing, spraying or dipping to form a thin film. All primers contain flammable solvents and therefore safety precautions are essential.

### 6.3.7 Specification compliance

Many standards have been written for silicone sealants. The most common standards are given in Table 6.9.

### 6.3.8 Specific areas of application

**6.3.8.1 Glazing.** There are many different glazing methods, and silicone sealants can be used either as the external weather-seal or as a total glazing system. Traditionally, the glazing industry has been the largest consumer of silicone sealants. Mainly acetoxycured systems of high modulus are used for the purpose. However, coated glasses may contain sensitive

**Table 6.9** Specification compliance standards for silicone sealants

Place	Standard
International	ISO 11600
United Kingdom	BS 5889: part A, Low-modulus part B, High-modulus
USA	ASTM C-920 TT-S-001543A TT-S-00230C
Germany	DIN 18545

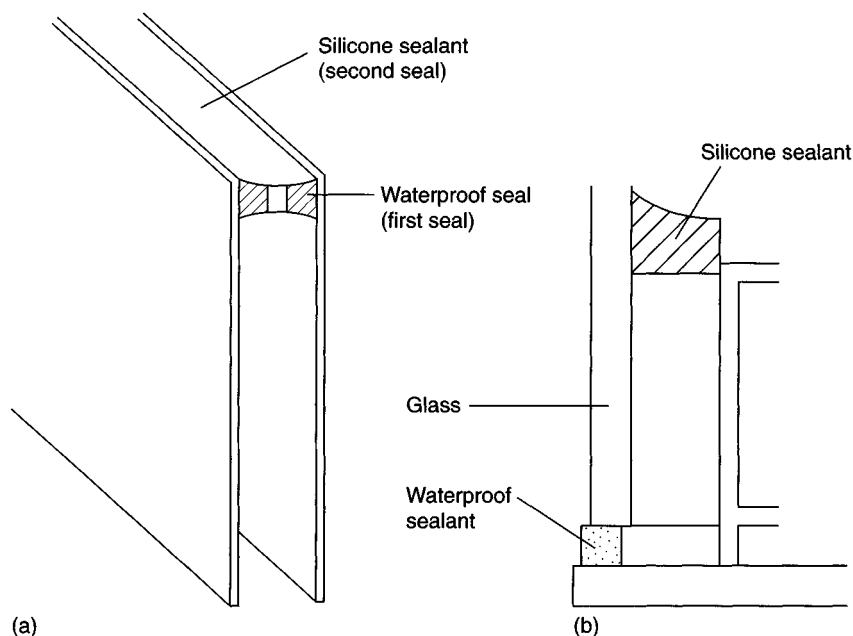
coatings, which restrict the use of an acetic-cured system. In such cases the use of neutral curing sealants is emerging.

The structural sealant glazing (SSG) system is a construction method for adhering, fixing and supporting glass and vitrified substrates, including windows as well as the external walls (curtain walls) of buildings, to the internal supporting materials by means of silicone sealants. In this way, a flush appearance is created on the exterior façade.

Key components of SSG are glass (clear, tinted, reflective, laminated, insulating), framing (anodised aluminium, coated aluminium, stainless steel) and, of course, silicone sealant as the preferred choice. The function of the sealant in the SSG system is to provide structural durability and waterproofing.

Single-component silicone sealants are more suitable for the job because of the simplicity of application. SSG systems are broadly of two types (Shin Etsu, 1994): two-sided and four-sided SSG systems. In two-sided systems two sides of the glass (top and bottom, or left and right) are supported by a frame. The other two sides are adhered and fixed to the internal supporting framework by means of silicone sealing materials. Thus the external facing becomes a striped plane. In the four-sided SSG system, all four sides of the glass are adhered and fixed to the internal supporting framework with silicone sealant. The exterior is totally flat.

The use of silicone sealant for insulating glass (double glazing) gives excellent adhesion to glass which is unaffected by UV radiation but which must be used with a waterproof sealant such as polyisobutylene to reduce moisture vapour transmission (MVT). The use of silicone sealant alone will result in water condensation inside the unit in a relatively short period of time and would permit water vapour to be absorbed into the unit and eventually exhaust the desiccant used in the space. The use of small beads of polyisobutylene as a primary seal (Figure 6.3) reduces the MVT to a very low number, thus correcting the one deficiency of silicone (PANEK and COOK, 1984). Sealants for SSG systems may be applied on



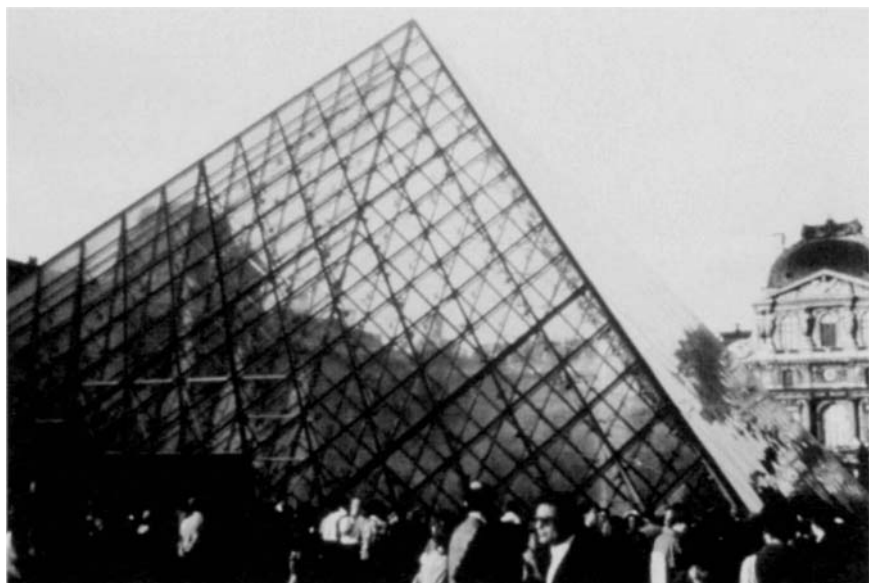
**Figure 6.3** The use first of a waterproof seal of polyisobutylene in double glazing to reduce the moisture vapour transmission; (a) outer view; (b) section

heat-reflecting glass and metals. By doing so, the air-conditioning load can be reduced, resulting in energy savings. A major job reference for silicone glazing sealants is illustrated in Figure 6.4.

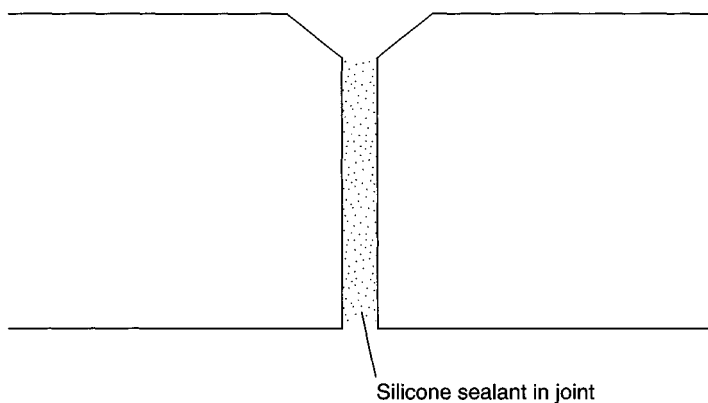
**6.3.8.2 Construction sealants.** Silicone sealants have proven to be very useful in a number of applications related to concrete construction (Figure 6.5). Systems based on neutral or alcoholic cure are suitable. Acetoxy-cured sealants are not suitable because of the evolution of acetic acid by-product, which reacts with calcium-bearing surfaces such as concrete and mortar, resulting in uncertain adhesion (Spells and Klosowski, 1981).

Joints in concrete construction can be classified broadly as either working joints or non-working joints. The difference between these two type of joints is the degree of designed movement. Working joints are primarily designed to accommodate movement associated with thermal expansion and contraction of the construction materials, for example:

- expansion joints, between two vertical masonry substrates;
- mixed joints, between two different types of substrates, such as metal to masonry.



**Figure 6.4** Silicone sealants used for the pyramid of the Louvre, Paris. Reproduced with permission from Rhône-Poulenc Silicones, Lyon, France



**Figure 6.5** The use of silicone sealant between two precast joints

Low-modulus neutral cure silicone sealants are suited to all kinds of working joints, ensuring that minimum stress is placed upon the sealant at its point of adhesion to the substrates (Figure 6.6).

In non-working joints the degree of movement is substantially less (5% or less). In these joints low-to-medium modulus silicone sealants are suitable.



**Figure 6.6** Silicone sealant in joints between granite. Reproduced with permission from Fosroc



**Figure 6.7** Application of silicone sealant in a sanitary area. Reproduced with permission from Rhône-Poulenc Silicones, Lyon, France

**6.3.8.3 Sanitary sealants.** Sanitary sealants prevent the infiltration of water between wall and sanitary installations. They are also resistant to mildew growth and common detergents.

Mid-to-high-modulus acetoxy-cured sealants are the most common. In certain applications, neutral cure silicones are also employed. Whatever the curing system, a sanitary sealant should be equipped with a fungicide. The sanitary field includes bathrooms (Figure 6.7), kitchens, refrigerators or cold storage rooms.

## **6.4 Silicone masonry water repellents**

Silicones have been used as masonry water repellents for more than 40 years. Mineral building materials absorb water and change their properties. The source of water is moisture, frost and efflorescence. The absorption of water depends on the porosity of the material. Water conveys destructive agents inside the building material, causing damage to the building. The absorption of water occurs by a number of routes (Wacker-Chemie, 1989), as will now be described.

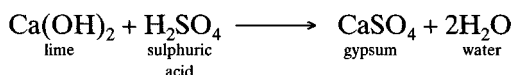


### 6.4.1 Capillary water absorption

This occurs as a result of direct contact of the building material with water, through:

- seepage into flooring;
- condensation;
- capillary condensation;
- hygroscopicity;
- water vapour permeability or water vapour diffusion.

Salts and gases can also penetrate into the building material. Salts penetrate by the capillary absorption of rainwater, especially where the building is exposed to splashes and where it is in direct and unprotected contact with the soil. Gases, especially oxides of sulphur (e.g. SO<sub>2</sub>, SO<sub>3</sub>), nitrogen (e.g. NO, NO<sub>2</sub>) and carbon (e.g. CO<sub>2</sub>) get into the material through diffusion. Whatever the case may be, the end result is the formation of salts inside the building material, leading to the conversion of insoluble binders into soluble salts:



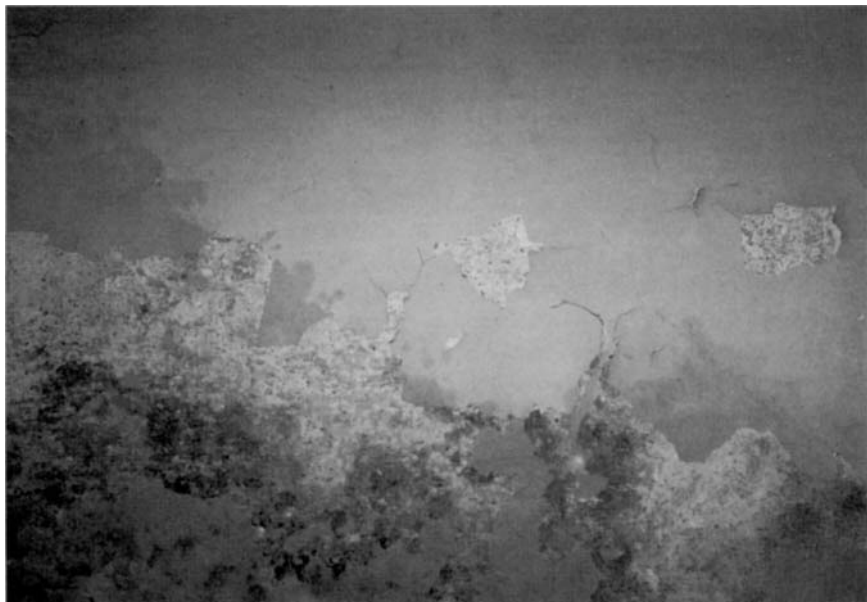
### 6.4.2 Damage caused by water and absorption of harmful substances

Whether the penetration is of water alone or of water with dissolved salt by any of the above-mentioned routes or of atmospheric gases, the end effect is damage to the building. The damage can be divided into six types (Wacker-Chemie, 1980a): damp patches, frost damage, chemical corrosion, salt damage, biological corrosion and loss of thermal insulation.

**6.4.2.1 Damp patches.** These are usually caused by differences in the capillary absorptivity of the masonry and are visible on exterior walls as uneven patchy areas after rain (Figure 6.8).

**6.4.2.2 Frost damage.** When the pores and the capillaries of the building material are frozen inside, they do not permit the non-destructive expansion of the frozen water, resulting in spalling (i.e. the disintegration of bricks, etc.) (Figure 6.9).

**6.4.2.3 Chemical corrosion.** Aggressive chemicals, acid waste and gases from fossilised fuels attack and destroy the binders of mineral building materials. A common example is the conversion of calcium carbonate into calcium sulphate (gypsum) by the action of sulphuric acid. This is accumulated on the surface of the building material producing hard destructive encrustations.



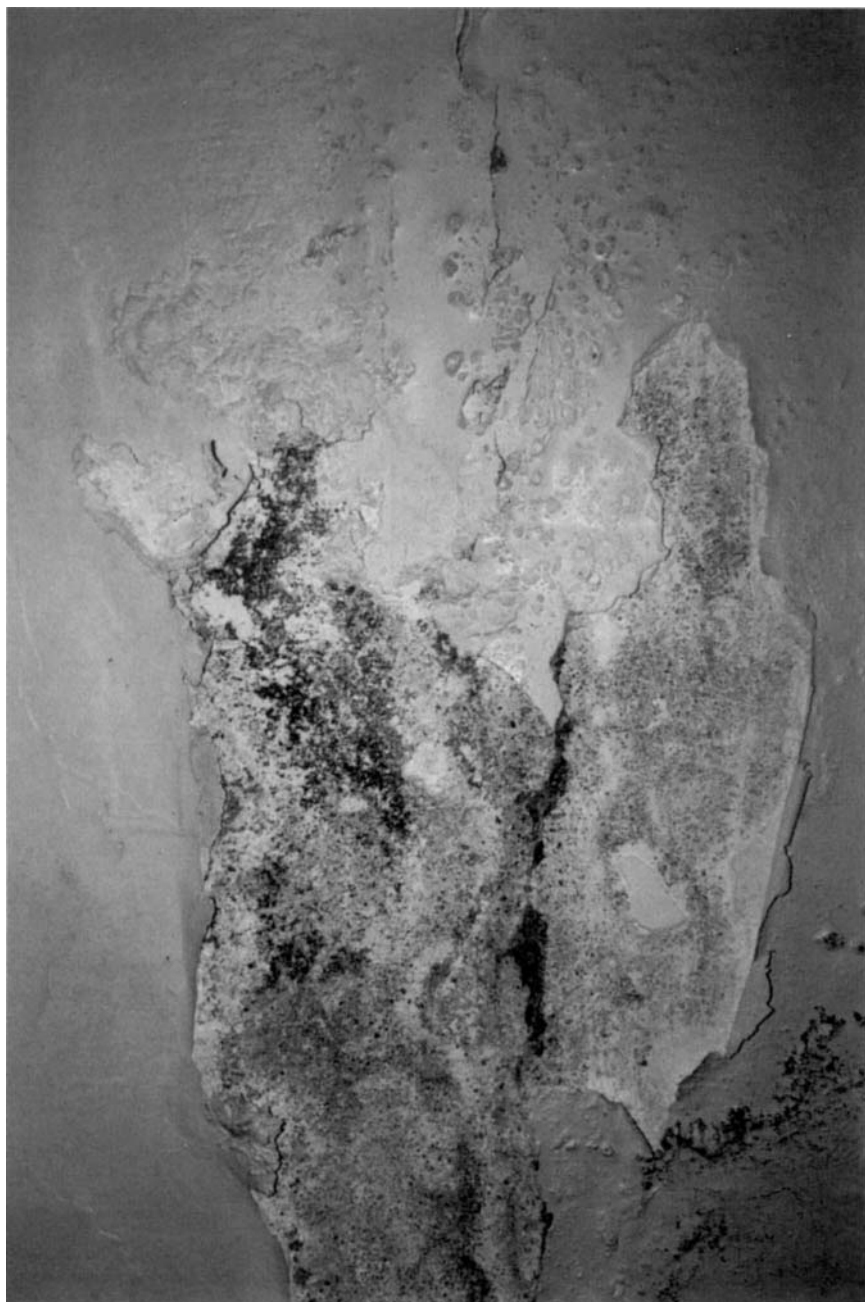
**Figure 6.8** Damp patches on a masonry wall

Carbon dioxide converts calcium hydroxide to calcium carbonate, gradually reducing the alkalinity of the concrete. The concrete then loses its ability to protect the steel reinforcing rods from corrosion and therefore these begin to rust.

Chloride ions at concentrations greater than about 0.4% wt/wt, calculated on the weight of the concrete, results in the corrosion of the reinforcing bars; ultimately, the surface of the concrete above the steel reinforcing rods breaks off.

**6.4.2.4 Damage caused by salts.** Soluble salts (e.g. soluble sulphates, chlorides and nitrates) from a variety of sources dissolve into water and penetrate into the building materials. Evaporation of water causes salt deposition inside the pores and capillaries, leading to crystallisation and hydrate formation. These processes cause expansion within the building material. When the pressure becomes high – between 20 N/mm<sup>2</sup> and 200 N/mm<sup>2</sup> – they destroy the building material (Figure 6.10).

**6.4.2.5 Biological corrosion.** Damp masonry surfaces allow the growth of micro-organisms such as bacteria, moulds, mosses, algae and lichens (Figure 6.11). With an efficient metabolism the separation of the products of metabolism can result in the deposition of salts. If walls are not treated the effect is an uninhabitable building.



**Figure 6.9** Signs of spalling arising from frost damage



**Figure 6.10** Damage caused by salts

**6.4.2.6 Loss of thermal insulation.** The presence of moisture causes a reduction in thermal insulation, leading to more condensation, making ground for all kinds of micro-organisms.

#### **6.4.3 Protective measures with silicones**

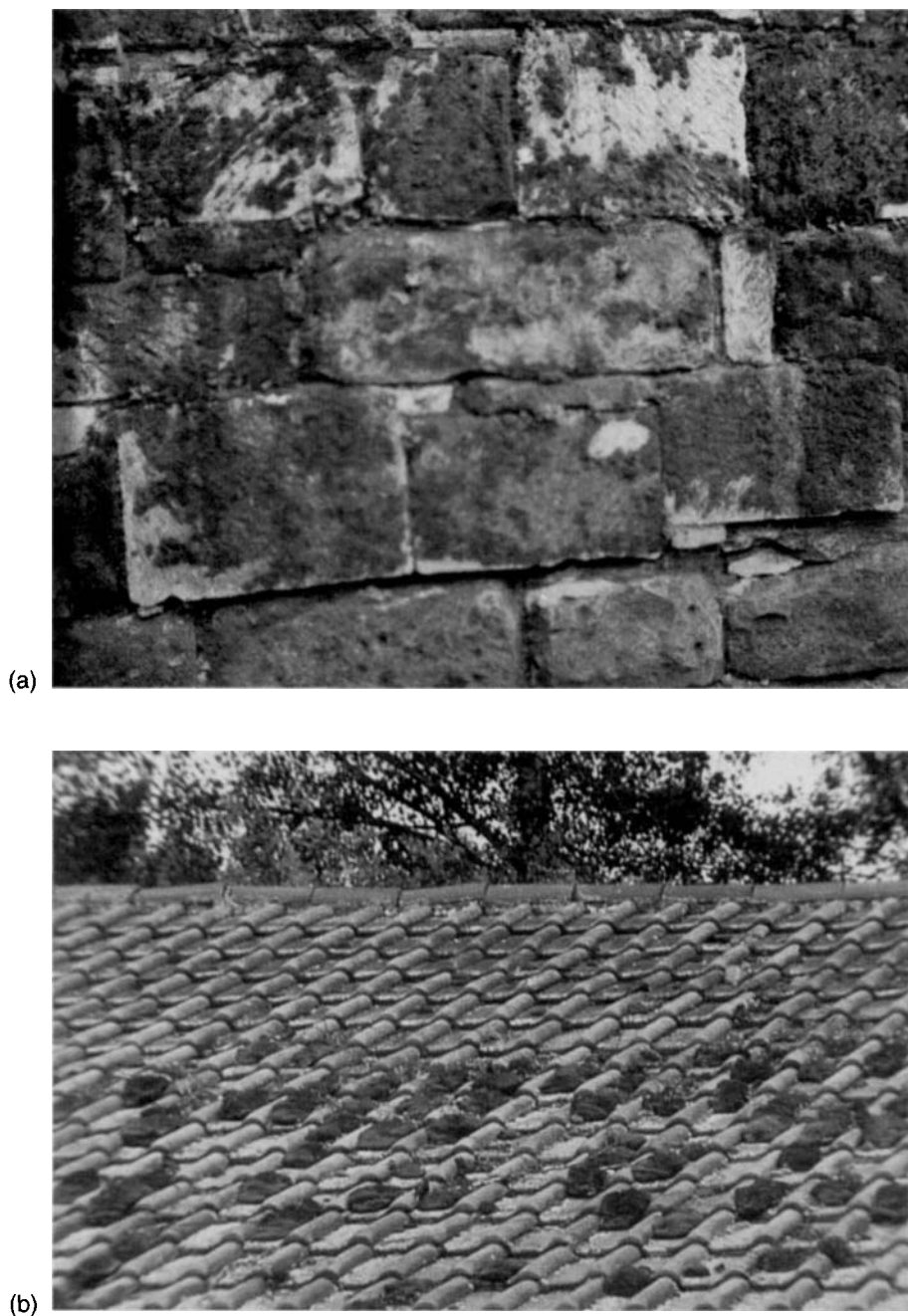
In order to prevent water from entering masonry or brickwork by capillary action, surface treatment is essential. This can be achieved by a number of methods:

- unpigmented solutions of resins such as epoxies, acrylics and similar resins;
- pigmented resin-based oil and emulsion paints;
- non-film forming water repellents such as silicone resins, silanes, siloxanes and siliconates.

The third method is the most efficient and effective. The details of these methods are given in Table 6.10. Figure 6.12 gives a comparison of untreated, sealed and silicone-impregnated systems.

Silicones satisfy the conditions of water repellency (Noll, 1968):

- they have a low surface tension, with the resulting spreading power;
- when applied to porous substrates they become distributed over the pore walls without sealing the passages;



**Figure 6.11** Micro-organisms growing on (a) a wall; (b) roof tiles

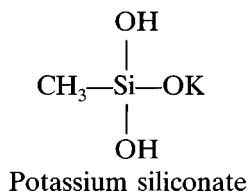
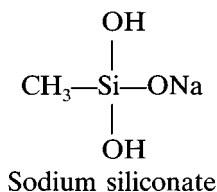
**Table 6.10** Preventive methods against the penetration of water into a building surface

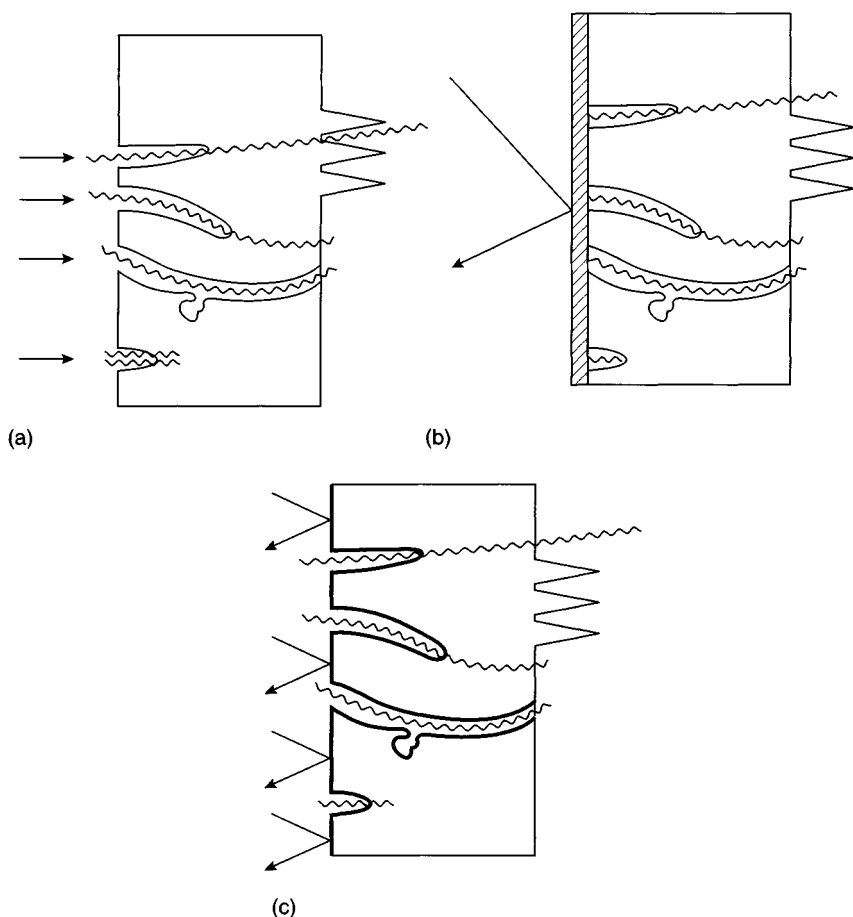
Method and remarks
<p>Use of unpigmented coatings (e.g. epoxies, acrylics, etc.)</p> <p>They can be used on glossy surfaces</p> <p>They are suitable for parts of buildings in constant contact with water under pressure</p> <p>They are unsuitable for façades</p> <p>They clog the pores</p>
<p>Use of pigmented coatings (e.g. oil and emulsion paints, synthetic resin-based plaster)</p> <p>They leave dry surfaces of pigmented films, the permeability of which to water and water vapour will depend upon the amount of synthetic resin present</p> <p>They clog the pores</p>
<p>Use of non-film-forming water repellents (e.g. siliconates, silicone resins, silicone and siloxanes)</p> <p>They eliminate or reduce the absorbancy without clogging the pores</p> <p>They do not affect the water vapour permeability and drying characteristics of the building material</p> <p>They are an effective means of water repellency for buildings</p> <p>They do not obstruct the exchange of gases</p>

- they do not change the pore cross-section of a material;
- they are non-staining;
- they reduce water and chloride ingress;
- they increase the freeze–thaw resistance;
- they allow the escape of water vapour from the structure;
- they are resistant to ice-melting compounds, fuels, oils and atmospheric contaminants;
- they are non-gloss;
- they possess long-lasting water repellency;
- they are UV resistant;
- they are suitable for use with natural stone, brick and exposed concrete.

#### 6.4.4 Types of silicone masonry water repellents

**6.4.4.1 Siliconates.** These have been in use since the early 1950s. They are water-soluble organosilane derivatives. The products are based on alkali metal methyl siliconates, for example sodium and potassium siliconates:





**Figure 6.12** Comparison of (a) untreated; (b) sealed; (c) silicone-impregnated systems. The untreated system is non-repellent to water (solid arrows) and is permeable to water vapour (wavy lines); the sealed system is water-repellent but impermeable to water vapour the silicone-impregnated system is water-repellent and permeable to water vapour

The use of potassium siliconates has become more common because of certain advantages over sodium siliconates such as greater frost resistance and better crystallising behaviour. They are used mainly for impregnating non-alkaline surfaces.

The mode of action of siliconates is based on the production of a water-insoluble silicone from a water-soluble monomeric compound after the evaporation of water by reacting at ambient temperature.

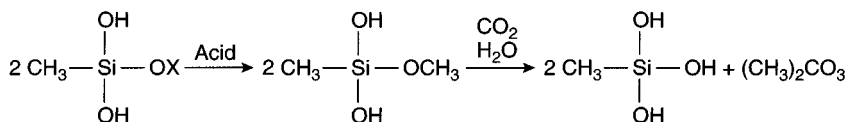
Higher alkylated siliconates have also been developed. They have very good alkali resistance and can be used for impregnating alkaline building materials such as concrete. Such higher alkylated siliconates are formed

by the addition of acids to aqueous solutions of sodium or potassium silicates, forming methyl silanols ([Figure 6.13(a)], which, in the presence of atmospheric carbon dioxide, change spontaneously via a methyl silicic acid intermediate, into polymethyl siloxanes by intermolecular condensation [Figure 6.13(b)].

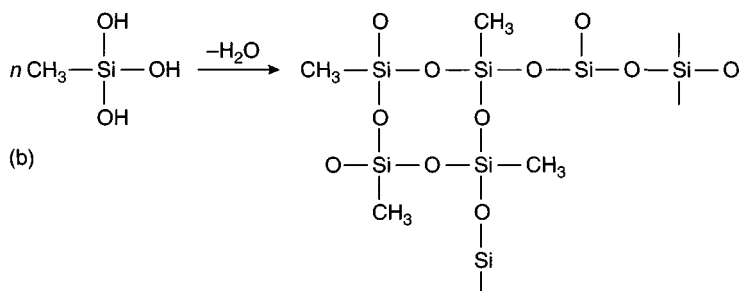
Silicates impart water repellency to aerated concrete, roofing tiles, facing bricks, floor tiles and damp substrates. Methyl silicates develop their water repellency only after chemically reacting with atmospheric carbon dioxide. A disadvantage is the relatively slow reaction with carbon dioxide, since the applied material remains water-soluble for some time and can therefore be washed out by rain.

**6.4.4.2 Silanes.** The use of silanes was exploited in the early 1970s. They are actually alkoxy silanes but are referred to in short as silanes. Silanes are not in themselves water-repellent but react with the moisture of the substrate to which they are applied, producing the active substance (Figure 6.14).

Silanes exhibit hydrophilic and hydrophobic properties. The molecule has both a non-polar and a polar component. The non-polar organic alkyl group is the vehicle for the water-repellent action. The effectiveness, durability and stability of the waterproofing agent depends on the size and nature of this group (Huls, 1991).



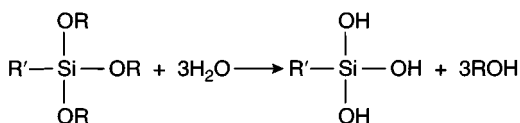
(a)



(b)

**Figure 6.13** Synthetic route of silicates to polysiloxanes: (a) reaction of silicate with acid to give a methyl silanol, followed by further decomposition in the presence of atmospheric carbon dioxide to methyl silicic acid and alkali carbonate; (b) formation of polysiloxanes from methyl silicic acid via intermolecular condensation. X = Na, K





**Figure 6.14** The reaction of silanane with moisture to give a water-repellent silanol.  
R' = water-repellent alkyl residue

The interplay of water-repellent alkyl group and hydrophilic alkoxy groups determines the molecular structure and the practical characteristics of the material (Huls, 1991). The alkoxy group determines the speed at which hydrolysis takes place and the compatibility of the material with damp mineral substrates and thus controls the depth of penetration into pores and capillaries and the reactivity in relation to the building material. The alkyl group determines the degree of waterproofing and therefore the material's resistance to chemical decay by the action of acids and substances which act as bases, including the metabolic products of fungi, bacteria, algae, etc., which are liable to attack damp building materials (subsection 6.4.2.5).

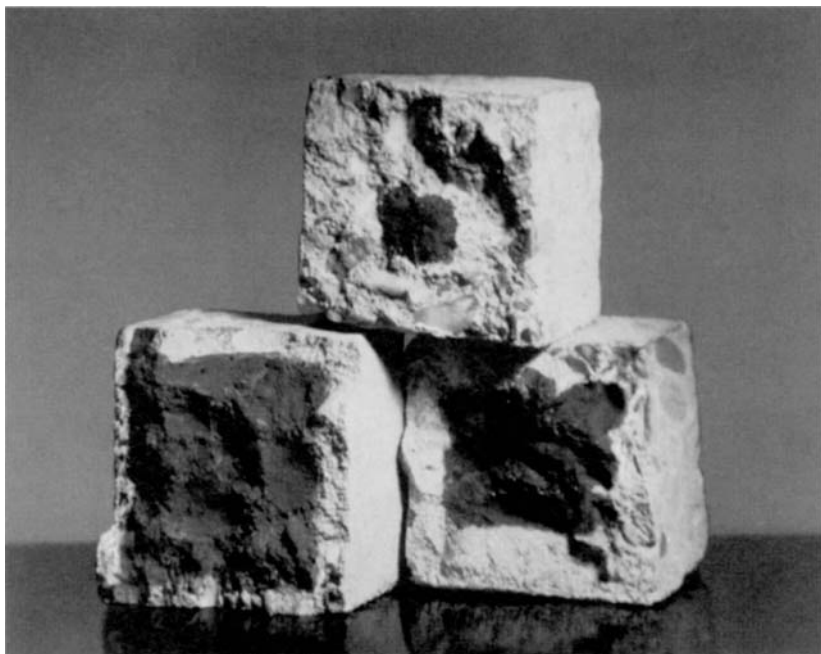
To be brief, higher alkylated, methoxy functional siloxanes are used mostly for the protection of masonry. Low molecular silanes give a good penetration depth. The main field of application is the impregnation of alkaline, poorly absorbing, still-wet materials.

Depending on the porosity of the building material and the condition of use, the depth of penetration of silanes varies from a few millimetres to a number of centimetres.

A frequent concern about the use of monomeric silanes is their volatility, which increases at high temperatures and also in windy conditions. In such cases, evaporation occurs after application before they are converted into the non-volatile water-repellent substance. Comprehensive and systematic investigations have shown that evaporation losses can be overcome by correct choice, to maximise the chances of success. Incorporation of catalysts accelerates the formation of active substances on the treated surface so that there is no appreciable loss from evaporation.

Solvent-free and solvent-based silane impregnating agents are commercially available. As a precautionary measure, application of silane-based impregnating agents should be avoided in direct sunlight, strong winds or in rain. To maximise the chances of success it is necessary to use a very high concentration of silane, up to 100% (Stockdale, 1991).

**6.4.4.3 Silicone resins.** Methyl silicone resins which can be diluted with organic solvents have been used for impregnating the façades of buildings since the mid-1950s. Surfaces impregnated with silicone resins show



**Figure 6.15** Depth of penetration: the upper block was impregnated with a silicone resin; the block on the lower left-hand side was impregnated with silane; the block on the lower right-hand side was impregnated with siloxane. Courtesy of HULS

very pronounced and long-lasting water repellency and are superior in this respect to all other impregnating agents.

Silicone resins can be used for impregnating strongly absorbent, poorly absorbent, light and dark substrates. Unlike the siliconates, silicone resins can be applied as often as desired to already impregnated surfaces since they do not repel organic solvents.

High-quality impregnating agents must fulfil four conditions:

- fast tack-free drying;
- greater depth of penetration (Figure 6.15);
- UV resistance;
- alkali resistance.

Since the molecular weight of silicone resins is much greater than that of silanes or siloxanes, they are not very penetrative. Penetration of more than 0.1 mm is considered unlikely under site conditions. The use of this type of material is therefore declining (Stockdale, 1991).

**6.4.4.4 Siloxanes.** These have a higher molecular weight than silanes, therefore they cannot achieve the same penetration depth. They reside

longer on the substrate and allow greater time for penetration and reaction. Siloxanes are normally used as 10%–20% solutions (Stockdale, 1991). Siloxanes are significantly cheaper than silanes and offer a similar degree of protection when used under the correct circumstances (Edwards, 1993). Siloxane-based water repellents are of two types: oleophobic and hydrophobic siloxanes and polymeric alkyloxysiloxanes.

*6.4.4.4.1 Oleophobic and hydrophobic siloxanes.* These are repellent to water (hydrophobic) as well as to organic liquids (oleophobic). Such products are used to impart antigraffiti or antiposter effects.

*6.4.4.4.2 Polymeric alkyloxysiloxanes.* These are considered as being halfway between silanes and oligomeric siloxanes. They do not have excellent penetrating power because of their high molecular weight. They remain tacky for a long time after application and tend to attract dirt. In view of these problems their use is decreasing and many companies have stopped their production altogether.

*6.4.4.5 Silicone resin emulsions.* With the aid of suitable emulsifiers and stabilisers, insoluble silicone resins can be converted into water-soluble emulsions and can be diluted with water. Such emulsions are used as water-repellent additives for plaster or silicate emulsion paints as well as for the surface treatment of mineral powders such as perlite, aerated concrete granules, and so on.

*6.4.4.6 Powdered products.* Powdered or solid silicone water repellents are based on methylsilsesquioxanes (Noll, 1968). They are added to mortar and plaster mixtures for effective water repellency. In chemical constitution, methylsilsesquioxanes are similar to polymethylsiloxanes, but because of their greater condensation they are insoluble in organic solvents. As compared with liquid impregnating agents, the addition of highly dispersed methylsilsesquioxane gives particles of silicone distributed uniformly through the whole depth of the plaster layer without the formation of a closed film.

Owing to the large quantity of silicone particles per unit area a similar effect to a closed film is obtained with respect to drops of water. Powdered repellents are also added to aqueous paints to make them water repellent.

### *6.4.5 Properties of good silicone water repellents*

Good silicone water repellents:

- have a high degree of water repellency;
- give permeability to air and water;

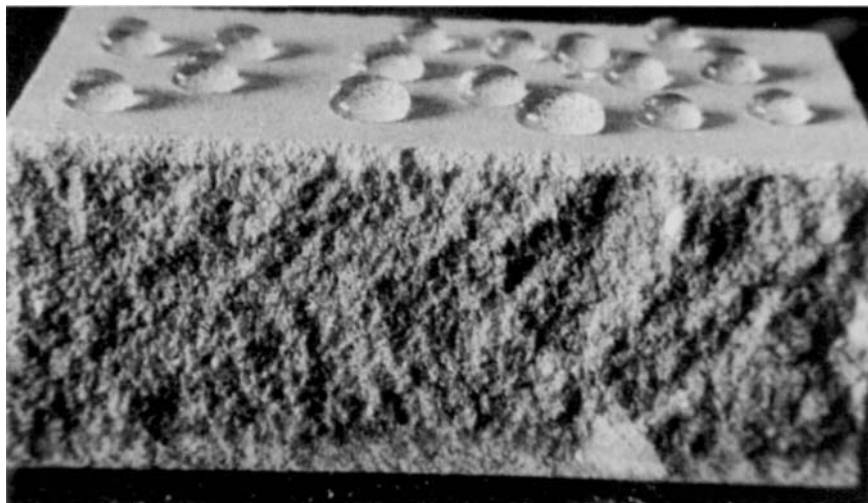
- prevent efflorescence;
- improve the frost resistance of building materials;
- are dust and soil repellent;
- have good durability.

#### 6.4.6 *Specific applications*

Uses for silicone water repellents are to:

- impart water repellency to façades (Figure 6.16);
- impart oil repellency to building materials;
- strengthen natural stones;
- protect concrete against frost and road salt damage as well as against corrosion of reinforcing steel rods.

In addition, surface treatment with silicone repellents prior to application of oil or emulsion paint prevents penetration of rain and moisture through hair-line cracks and thereby prevents damage to the paint film, greatly improving the paint film's impermeability to water without reducing its water-vapour permeability. Also, addition of silicone emulsion to whitewash or application of a colourless impregnating agent to a whitewashed surface, makes possible a high-quality weather-resistant finish. Further, a colourless impregnating agent can be applied to silicate paint finishes to give very good water resistance and to reduce the tendency for the surface to accumulate dirt.



**Figure 6.16** Building material impregnated with water-repellent silicone. Reproduced with permission from Rhône-Poulenc Silicones, Lyon, France

Silicate emulsion paints are made water-repellent by

- application of colourless silicone primes;
- addition of silicone masonry water repellent to the paint;
- application of colourless impregnating agent over the paint.

*6.4.6.1 In-plant impregnation of low-fired ceramic products.* Low-fired ceramic products such as roof tiles, facing tiles and unglazed floor tiles are made water repellent by immersing them in dilute silicone masonry water repellents thereby preventing efflorescence and imparting water repellency (Wacker-Chemie, 1982). Prefabricated concrete components, plaster of paris and aerated concrete can also be treated in this way.

*6.4.6.2 Impregnation of exterior walls.* Impregnation is carried out in order to protect vertical surfaces (exterior walls, Figure 6.17) or sharply sloping surfaces (rooves) against rain (Wacker-Chemie, 1983). Addition of dry powders to mineral finishing plaster imparts water repellency to plasters.



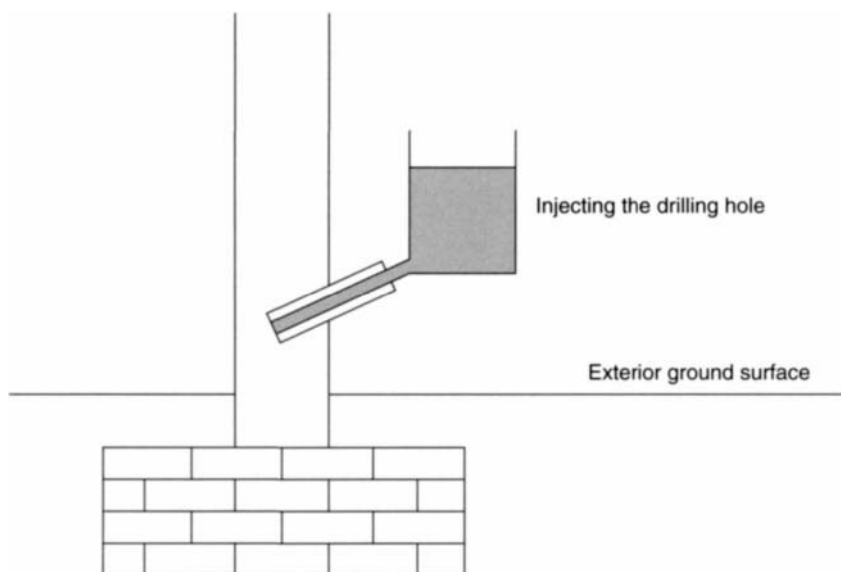
**Figure 6.17** Exterior walls of a building, impregnated with silicone masonry water repellent.  
Reproduced with permission from Fosroc

**6.4.6.3 Production of damp courses.** A damaged damp course will allow moisture to travel up the walls of a building, causing major damage to the masonry, the plastered wall and painted surfaces. Such problems are common in old buildings. The preventive measure is to produce a new damp course by drilling holes into the walls just above ground level and then injecting silicone masonry water repellent (Figure 6.18), (Wacker-Chemie, 1980a).

**6.4.6.4 Application methods for the impregnating agent.** The durability of the water-repellent effect depends not only on the product quality but also on the depth of penetration achieved. In order to ensure sufficient penetration, the impregnating solution should be applied by spraying or flooding. Airless spraying techniques can also be used provided the seals and hoses are solvent-resistant.

Best results are achieved with low spraying pressures. The distance between the nozzle and the wall should be 5–10 cm and the impregnating solution should be applied until the area being treated will absorb no more and the solution runs down 40–50 cm. The spraying nozzle is then slowly moved on horizontally.

Two applications of impregnating solution are sufficient both for strongly absorbent and for less absorbent materials. The second application can take place after the absorption of the first one, that is, when the



**Figure 6.18** The production of a new damp course in a wall by injection with silicone masonry water repellent

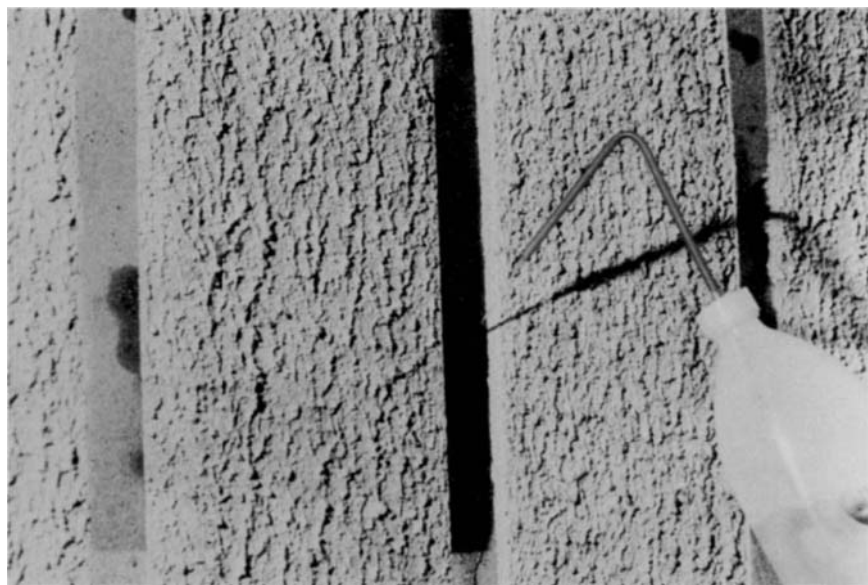
treated surface is no longer glossy. Smaller areas or walls with many windows can be impregnated by brush or roller. Impregnated surfaces can be overpainted with silicone paints or with most emulsion paints. However, preliminary tests are advisable.

### 6.5 Silicone coatings

The unique combination of properties, when coupled with water resistance and good low-temperature properties, arising from the relatively low glass transition temperature, have made silicones the material of choice for numerous coating applications and they have become an essential part of the paint industry's armoury for speciality coatings.

Silicone coatings used in the construction industry are one-component silicone rubber dispersions. They cure at room temperature, vulcanisation being effected by the influence of atmospheric humidity. The process evolves various primary aliphatic amines and the solvent evaporates.

Silicone coatings are suitable for expansion joints in concrete, mortars and on metallic rooves (Figure 6.19). Such coatings possess outstanding resistance to weathering, ageing, radiation, ozone and temperature and they are inert to industrial atmospheres, salt solutions, dilute acid and alkaline solutions as well as to nearly all other aggressive media in



**Figure 6.19** Silicone coating in building applications. Reproduced with permission from Rhône-Poulenc Silicones, Lyon, France

aqueous systems under normal temperature conditions. However, organic solvents may cause a more or less reversible swelling (Wacker-Chemie, undated).

Silicone coatings are marketed in various colours as well as in a transparent form. Where high-temperature resistance is required inorganic pigments are used.

Silicone coatings retain their permanent flexibility even at low temperatures. By virtue of this property they are used to bridge small cracks in construction and allow primary movement of cracks. They are used for coating construction parts and buildings made from mineral construction materials, plastics, wood or metal, for insulation or for preventing corrosion. Silicone coatings have been successfully used in the protection of monuments. In this case transparent coatings are used. They also considerably reduce the soiling of façades (Wacker-Chemie, 1980b).

Like other coatings, excellent surface preparation is necessary to make them free from dust, grease, tar, bituminous substances, laitance and adhering friable particles. Application can be made by brush, roller or by spraying. A coating thickness of up to 1 mm does not cause any flow of material in vertical applications. The use of primer ensures excellent adhesion. Some important applications of silicone coatings are as follows. They can be used as:

- a waterproof treatment for outside walls or rooves;
- a protective coat on concrete to guard against injury from salts;
- weather-resisting and waterproofing treatment for building materials;
- rust and corrosion resistant coatings on metallic rooves;
- linings for various plant apparatuses;
- rust and corrosion resistant coatings on tank surfaces.

Before this section is concluded, it is important to mention that increasing environmental regulations have resulted in coatings with low volatile organic contents (VOC), high-solid resins as well as water-borne systems without affecting the performance (Reti, 1993). The use of solvented silicone coatings is declining. In the coming few years one can expect the use of these materials to become obsolete. In today's world the use of solution type and aqueous type silicone coatings is becoming more common. The latter type can be diluted with water without breaching safety or sanitation laws (Shin Etsu, 1995).

## 6.6 Health and safety

Some of the compounding ingredients such as the catalyst may be an irritant or toxic. Also, by-products evolved during the curing of the elastomer may be an irritant (e.g. acetic acid is evolved in the acetoxycured system).



Solvented silicone systems may be hazardous with regard to health or fire. Further, primers are flammable and require care in handling. Methylchlorosilanes are flammable and corrosive because of the liberation of hydrochloric acid on hydrolysis; other chlorosilanes are less flammable but are hazardous chemicals and can irritate the eyes, respiratory organs and skin. Protective gloves should be used. The material should not be allowed to make contact with the eyes or skin. Inhalation of vapours should be avoided especially in systems which evolve irritant by-products such as acetic acid or amines.

Flammable materials such as primers should be stored away from heat and from sources of static charges. Adequate ventilation should be ensured during use, and smoking, eating or drinking should not be practised during work.

Respirators are advisable where vapour or aerosols are used or where ventilation is inadequate; safety goggles and gloves should always be used.

With all products, in case of contact with the eyes rinse out immediately with a large quantity of water and consult an eye specialist. After contact with skin wash immediately with a large quantity of water. If inhalation occurs take the affected person into the fresh air and consult a doctor if necessary.

Do not allow the material to get into the groundwater or sewerage system. Disposal should be carried out according to the local regulations. Material safety data sheets should always be referred to before using any product.

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## **7 Polysulphides in the construction industry**

### **7.1 Introduction**

In the construction sector, polysulphide technologies are available in the form of joint sealants and protective coatings. Until the late 1970s and early 1980s polysulphides were widely used as construction, civil engineering and insulated-glass sealants. Competition arrived with the introduction of polyurethanes and silicone sealants, which offer better ultraviolet (UV) and ozone resistance and a wider colour range. However, some recent advances in polysulphide technology have led to a resurgence in the popularity of polysulphide systems as sealants and protective coatings. The properties that make them useful are:

- excellent oil and solvent resistance;
- water and sewage resistance;
- low-temperature and high-temperature resistance.

The potential market for polysulphides is for water-industry sealants, and fuel-resistant sealants and coatings for secondary containments. As a construction, civil engineering and insulating-glass sealant polysulphides have a poor to fair market share. Table 7.1 summarises the specific applications of polysulphide systems in the construction industry.

### **7.2 Properties**

#### *7.2.1 Solvent resistance*

The properties of polysulphide polymers are summarised in Table 7.2. Cured polysulphide systems possess excellent resistance to most solvents and mild inorganic acids. The solvent resistance depends on the sulphur content of the polymer. Table 7.3 compares the resistance of various liquid polysulphide polymers to a variety of solvents and chemical solutions. However, these data cannot be considered as absolute because the resistance is to some extent dependent on the efficiency of cure. Volume swell values below 40% illustrate excellent resistance. Those between 40% and 90% illustrate fair to good resistance whereas values above 90% may be only fair or even unsatisfactory (Thiokol Chemical Co., 1969).

**Table 7.1** Specific application areas of polysulphide systems in the construction industry

Product and property	Application area
Sealant:	
Oil and solvent resistance	Jet fuel aprons Airport pavements Petrol stations, to prevent the contamination of groundwater Areas where spillage of aircraft fuel or hydraulic directive fuel is common Areas where solvent spillage is common Chemical plants and refineries Chemical warehouses Pavings associated with motorways and bridge decks
Water and sewage resistance	Potable water tanks Waste water tanks Irrigation canals Sewage storage and treatment tanks
High-temperature resistance	In building structures to minimise the risk of fire e.g. expansion and compression joints, construction gaps, fire protection panels, fire doors around cable, pipe penetration
Ultraviolet radiation and ozone resistance, low-temperature resistance	Expansion and compression joints Building and civil engineering application
Coating:	
Oil and solvent resistance	To prevent the spillage of secondary-containments above or below ground level in fuel storage tanks

**Table 7.2** Properties of polysulphide polymers

Property	Typical value or description
General chemical structure	$\sim [R-S]_x \sim$ $R = (CH_2Cl)_2$ or $(CH_2(OCH_2CH_2Cl))_2$
Service temperature (°C)	-50 to 95
Cold resistance	Fair
Ageing resistance	Excellent
Sunlight resistance	Medium
Ozone resistance	Excellent
Heat resistance	Poor
Flame resistance	Poor
<i>Fluid resistance:</i>	
Aliphatic	Excellent
Aromatic	Excellent
Mineral resistance	Excellent
Animal or vegetable resistance	Excellent
Water resistance	Good to excellent <sup>a</sup>
Electrical resistance	Moderate
Optimum properties	Maximum oil or solvent resistance

<sup>a</sup> Depends upon the percentage of polymer and curing agent used.

Systems that are not properly compounded have somewhat poor solvent resistance. Some plasticisers, fillers and other compounding ingredients can be hydrophilic; therefore, it is necessary to screen the components to obtain a perfect compound (Panek and Cook, 1984).

By virtue of their solvent-resistant property, polysulphide polymers are used extensively as integral fuel tank sealants. The construction industry utilises this property mostly in sealants in jet fuel aprons, laboratory floors, airport pavements and for use in petrol stations. Specific applications will be discussed separately in section 7.4.

### 7.2.2 Low-temperature properties

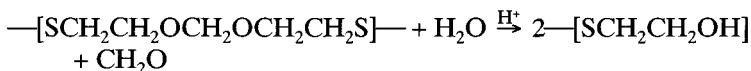
The nature of the hydrocarbon moiety and the length of the polysulphide chain are the deciding factors for the glass transition temperature ( $T_g$ ). The longer the hydrocarbon component of the polymer, the lower the value of  $T_g$  (Ellerstein and Pertozzi, 1982). The glass transition temperatures of polysulphide polymers are given in Table 7.4.

The use of bis (2-chloroethyl) formal as the predominant monomer in the manufacture of polysulphides results in the formation of polymers with very good low-temperature properties. The glass transition temperature of these disulphide polymers is  $-59^\circ\text{C}$ . Furthermore, there is no tendency in these polymers to crystallise at a temperature above the glass transition point. A glass transition temperature of  $-59^\circ\text{C}$  applies to all the commercial liquid polysulphide (LP) polymers.

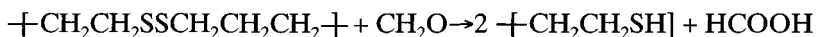
### 7.2.3 High-temperature properties

The thermal stability of polysulphide polymers is governed by the composition of the polymer backbone and by the curing system. LP liquid polymers which contain a repeating ethylene formal disulphide structure are resistant to temperatures up to  $100^\circ\text{C}$ . Temperatures substantially above  $100^\circ\text{C}$  result in thermal degradation of the polymer (e.g. weight loss along with hardening) (Rosenthal and Berenbaum, 1957). The degradation process can be explained by the following series of reactions.

1. Acid-catalysed hydrolytic attack occurs on the formal group by trace amounts of water:



2. Free formaldehyde is released from the above reaction, which in turn acts as a reducing agent on the polymer disulphide bonds to bring about a reduction into thiol with the formation of formic acid:



**Table 7.3** Solvent and chemical resistance of cured liquid polysulphide (LP) compounds.<sup>a</sup> Source: Morton International Ltd, Coventry, UK

Solvent	Volume swell (%)			Solvent	Volume swell (%)		
	LP-2	LP-3	LP-32		LP-2	LP-31	LP-32
<b>Aliphatic and aromatic fuels, oils and solvents:</b>				<b>Halogenated hydrocarbons:</b>			
SR-6	8 (OK)	11 (OK)	21 (OK)	Carbon tetrachloride	55 (F)	62 (F)	7 (F)
SR-10	-4 (OK)	-5 (OK)	11 (OK)	Ethylene dichloride	440 (NG)	501 (NG)	60 (NG)
ASTM reference fuel A	-7 (OK)	-3 (OK)	-1 (OK)	Trichloroethylene	275 (NG)	320 (NG)	401 (NG)
ASTM reference fuel B	1 (OK)	5 (OK)	+12 (OK)	Perchloroethylene	28 (OK)	33 (OK)	43 (OK)
ASTM Oil 1	-7 (OK)	+5 (OK)	+1 (OK)	Monochlorobenzene	270 (NG)	350 (NG)	474 (OK)
ASTM Oil 2	1 (OK)	7 (OK)	12 (OK)	<b>Ketones and ethers:</b>			
Turpentine	5 (OK)	8 (OK)	11 (OK)	Acetone	19 (OK)	35 (OK)	50 (F)
Skydrol™	35 (OK)	44 (F)	59 (F)	Methyl ethyl ketone	56 (F)	64 (F)	87 (F)
Motor oil	-5 (OK)	-3 (OK)	-1 (OK)	Methyl isobutyl ketone	24 (OK)	30 (OK)	36 (OK)
JP-5	-5 (OK)	-1 (OK)	2 (OK)	Ethyl Cellosolve™	12 (OK)	20 (OK)	28 (OK)
<b>Hydroxyl compounds:</b>				Butyl Cellusolve™	12 (OK)	15 (OK)	8 (OK)
Ethyl alcohol (denatured)	-5 (OK)	-2 (OK)	2 (OK)	Dibutyl ether	500 (NG)	550 (NG)	605 (NG)
Butyl alcohol	-4 (OK)	-3 (OK)	-2 (OK)	Butyl Carbitol™	12 (OK)	15 (OK)	19 (OK)
Methyl alcohol	6 (OK)	4 (OK)	3 (OK)	<b>Vegetable and wood oils:</b>			
Diacetone alcohol	12 (OK)	15 (OK)	10 (OK)	Linseed oil	-4 (OK)	-2 (OK)	0 (OK)
Ethylene glycol	-3 (OK)	1 (OK)	4 (OK)	Cottonseed oil	-7 (OK)	-5 (OK)	-3 (OK)
Glycerol	-2 (OK)	0 (OK)	1 (OK)	Castor oil	-8 (OK)	-5 (OK)	-2 (OK)
2-Ethyl hexanol	-20 (OK)	0 (OK)	1 (OK)	Corn oil	-6 (OK)	-5 (OK)	-4 (OK)
Isopropyl alcohol	-5 (OK)	-1 (OK)	2 (OK)	White pine oil	14 (OK)	15 (OK)	17 (OK)
				Soya bean oil	-5 (OK)	-2 (OK)	0 (OK)

**Esters and plasticisers:**

Ethyl acetate	40 (OK)	51 (F)	64 (F)
Butyl acetate	30 (OK)	33 (OK)	48 (F)
Tributoxy ethyl phosphate	6 (OK)	12 (OK)	17 (OK)
Dibutyl phthalate	30 (OK)	42 (OK)	55 (F)
TP-90B™ plasticiser	12 (OK)	20 (OK)	26 (OK)
TP-95™ plasticiser	33 (OK)	40 (OK)	51 (F)
Dibutyl sebacate	0 (OK)	4 (OK)	8 (OK)
Diocetyl phthalate	28 (OK)	30 (OK)	33 (OK)
Butyl Cellosolve™ adipate	33 (OK)	33 (OK)	36 (OK)
Propylene glycol ricinoleate	-3 (OK)	1 (OK)	5 (OK)
Diocetyl adipate	-6 (OK)	-3 (OK)	0 (OK)

**Aromatic hydrocarbons:**

Benzene	195 (NG)	220 (NG)	314 (NG)
Toluene	95 (F)	105 (NG)	138 (NG)
Xylene	39 (OK)	42 (OK)	61 (F)

**Acid,<sup>b</sup> base and other solutions:**

Sulphuric acid			
10%	1 (OK)	1 (OK)	1 (OK)
20%	0 (OK)	1 (OK)	1 (OK)
50%	(R)	(R)	(R)
100%	(R)	(R)	(R)
Nitric acid			
10%	(R)	(R)	(R)
50%	(R)	(R)	(R)
Hydrochloric acid			
10%	0 (OK)	1 (OK)	1 (OK)
30%	0 (OK)	3 (OK)	5 (OK)
37%	(R)	(R)	(R)
Sodium hydroxide solution			
10%	0 (OK)	0 (OK)	0 (OK)
20%	-1 (OK)	0 (OK)	1 (OK)
50%	-1 (OK)	0 (OK)	1 (OK)
Sodium chloride solution			
3%	0 (OK)	0 (OK)	1 (OK)
10%	2 (OK)	1 (OK)	1 (OK)
36%	2 (OK)	1 (OK)	10 (OK)
Copper sulphate solution			
10%	3 (OK)	3 (OK)	3 (OK)
14%	2 (OK)	3 (OK)	5 (OK)

<sup>a</sup> All specimens were immersed in solution for 30 days at 80°F (27°C). Test method per ASTM D471-62T, Method B.

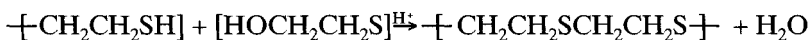
<sup>b</sup> The percentages shown for the acids are the dilutions of the concentrated acid.

Note: OK = excellent performance capability; F = fair to good performance capability; NG = not good; R = reverted.

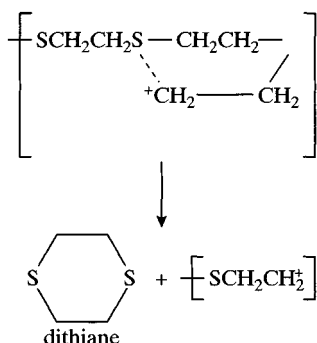
**Table 7.4** Glass transition temperatures ( $T_g$ ) of various polysulphides. Source: Morton International Ltd., Coventry, UK

Polymer	Structure	$T_g$ ( $^{\circ}\text{C}$ )
Poly(ethylene disulphide)	$(\text{SCH}_2\text{CH}_2\text{S})_n$	-27
Poly(ethylene tetrasulphide)	$(\text{S}_2\text{CH}_2\text{CH}_2\text{S}_2)_n$	-24
Poly(ethylether disulphide)	$(\text{SCH}_2\text{CH}_2\text{OCH}_2\text{CH}_2\text{S})_n$	-53
Poly(ethylether tetrasulphide)	$(\text{S}_2\text{CH}_2\text{CH}_2\text{OCH}_2\text{CH}_2\text{S}_2)_n$	-40
Poly(ethylformal disulphide)	$(\text{SCH}_2\text{CH}_2\text{OCH}_2\text{OCH}_2\text{CH}_2\text{S})_n$	-59
Poly(pentamethylene disulphide)	$(\text{SCH}_2(\text{CH}_2)_3\text{CH}_2\text{S})_n$	-72
Poly(hexamethylene disulphide)	$(\text{SCH}_2(\text{CH}_2)_4\text{CH}_2\text{S})_n$	-74
Poly(butylformal disulphide)	$(\text{SCH}_2(\text{CH}_2)_3\text{OCH}_2(\text{CH}_2)_3\text{S})_n$	-76
Poly(butylether disulphide)	$(\text{SCH}_2(\text{CH}_2)_3\text{OCH}_2)_n\text{S}$	-76

3. Formic acid further catalyses the hydrolysis at the formal group; the mercaptan terminal groups can react with a hydroxyl group to yield a monosulphide bond:



In the case of polymers based on bis(2-chloroethyl) formal the thermally decomposed polymers exhibit a plastic-like, brittle, non-elastomeric consistency which is due to the formation of the cyclic crystalline compound dithiane (Berenbaum, 1969):



Another cause of thermal instability arises from the incorporation of metals into the polymer backbone. This process is believed to be the formation of a small amount of lead thiolate group when  $\text{PbO}_2$  is used as a curing agent. In this reaction the lead mercaptide segment is formed in the polymer chain. The formation of mercaptide-disulphide, which occurs as a consequence of the presence of these groups, has a profound effect on the compression set of the product. In order to minimise this effect a small quantity of sulphur is added to the compound. This converts the lead mercaptide groups to lead sulphide and polymer disulphide links. Systems cured with tellurium dioxide, manganese dioxide and chromate salts were found to be particularly useful as they do not form



**Table 7.5** The symptoms and reasons for the thermal degradation effect of high temperature on ethylene formal disulphide polymers

Symptom	Reason
Weight loss and hardening of polymer	Formation of a trace amount of acidity
Loss of compression set resistance and some polymer volatilisation	Formation of lead mercaptide segment in the polymer chain when $\text{PbO}_2$ is used as a curing agent

mercaptides. Polysulphide systems cured with these agents can provide continuous service at 100°C to 125°C and intermittent service at 125°C to 150°C (Berenbaum, 1969). Table 7.5 summarises the high-temperature effects on ethylene formal disulphide polymers.

#### 7.2.4 Stress relaxation (viscoelastic properties)

This property is due to random interaction of trace residual thiol groups with the polymer disulphide groups. Another cause is the interchange between disulphide group neighbouring chains. The energy of activation for this interchange process is 100 kJ/mol for disulphide and tetrasulphide polymers. The rate of stress relaxation depends on temperature, UV light and catalyst. The viscoelastic properties of polysulphide polymers are discussed in detail by Tobolsky and Macknight (1965). On rapid application of stress, the cross-linked rubbers behave as conventional elastomers. Under fixed strain, the interchange process sets in to relieve the stress.

#### 7.2.5 Tensile properties

The tensile modulus of polysulphide polymers is enhanced with additional cross-linking agent and filler loading. It decreases with plasticisation. The presence of suitable reinforcing pigments gives adequate tensile and elongation properties.

#### 7.2.6 Elongation

This property is useful in the case of joint sealants where a movement accommodation factor is the main concern. Elongations of 100% are acceptable. However, it is possible to formulate polysulphides with ultimate elongations in excess of 1000%.

#### 7.2.7 Ageing and weathering

Polysulphide systems were found to be durable over long periods and to be resistant to ozone, sunlight and weathering.

### 7.3 Polysulphide sealants

Polysulphide sealants were introduced to the construction market in the 1950s with the advent of curtain-wall high-rise structures. The polysulphides commonly used in the manufacture of sealants have an average molecular weight between 4000 and 8000 and a viscosity range between 400 and 1100 poise. The percentage of cross-linking agent ranges from 0.2 to 2.0 and the average mercaptan content ranges from 1.10% to 1.75% (Maslow, 1982). A list of the various raw materials (other than liquid polysulphide polymers) used in formulating a polysulphide sealant is given in Table 7.6. It is important to note that a polysulphide sealant will perform only as well as its compound allows. Sealants made with too much volatile plasticisers can shrink, craze and crack with time. If the volatile loss is high, then the hardness will also increase greatly, causing eventual adhesive or cohesive failure with subsequent movements.

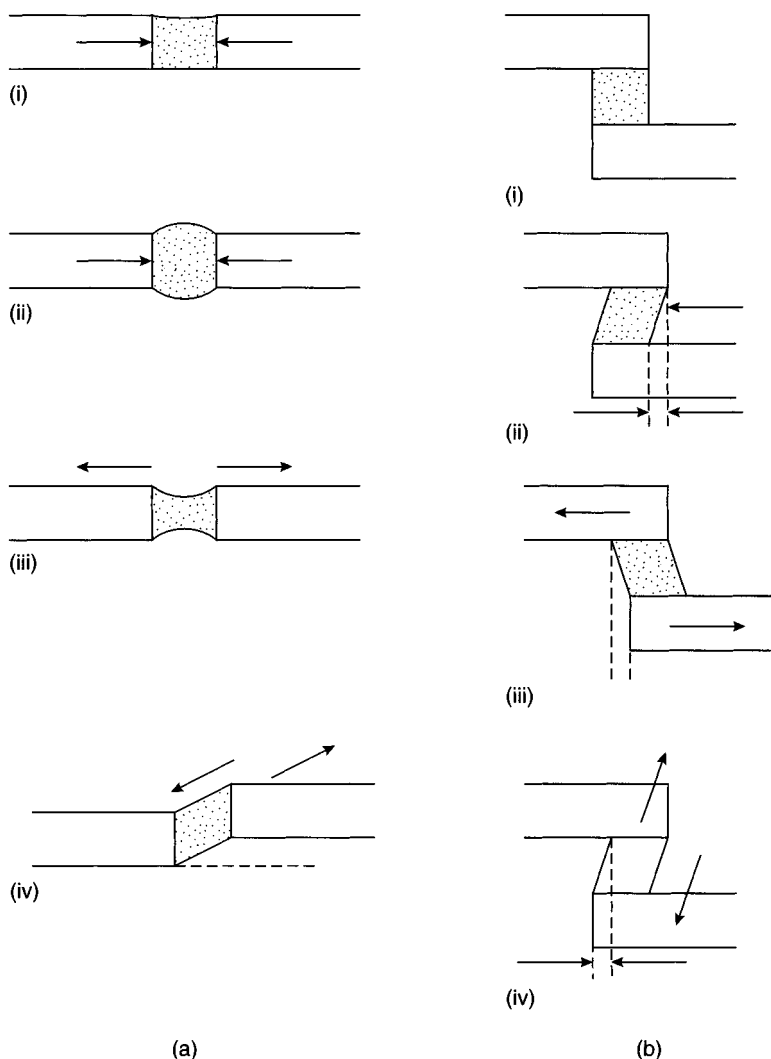
Polysulphide sealants were used in building structures for a long time before a standard specification was developed for such uses. ASA-A116.1 was the first specification for building sealants written by the Building Trade Specification Committee in 1956. Later, several specifications were designated by different societies for one-component and two-component systems. The specifications will be mentioned in the following. Apart from polysulphides these specifications also refer to urethane and silicone sealants

High-performance characteristics are offered by polysulphide sealants with a maintenance-free service life in excess of 15 years. Good evidence exists to show that these sealants, when properly formulated and applied, have a real service life in excess of 40 years (Lowe, 1994a).

Polysulphide sealants fulfil the requirements of expansion joints in concrete structures such as bridges, subways and high-rise buildings where a high level of joint movements occur. They are suitable for compression movement, extension movement and shear movement in butt joints as well as overlap joints. The only joint in which a sealant can accommodate more than +50% movement is in lateral shear in an overlap joint. In all other joint designs the sealant cannot take more than  $\pm 25\%$  move-

**Table 7.6** Secondary ingredients in polysulphide sealants

Function	Raw materials
Adhesion promoter	Epoxies, hydrocarbon resins, phenolic resins, silanes
Filler	Coated ground or precipitated calcium carbonate, clays, silica flour, carbon black
Pigment	Titanium dioxide
Plasticisers	Chlorinated paraffin, hydrogenated terphenyls, phthalate esters, dipropylene glycol dibenzoate
Thixotropes	Bentonites, fumed silicas, hydrogenated castor oils



**Figure 7.1** Joint movements associated with polysulphide sealants, by type of joint: (a) butt joints showing (i) normal configuration, (ii) 25% compression, (iii) 25% extension, (iv) 25% vertical shear; (b) overlap joints showing (i) normal configuration, (ii) 50% lateral shear compression, (iii) 50% lateral shear extension, (iv) 25% vertical shear

ment. Figure 7.1 illustrates various joint movements associated with polysulphide sealants.

Polysulphide sealants are of two types, namely two-component sealants and one-component sealants. These will each be discussed in turn in the following two sections.

### 7.3.1 Two-component sealants

In this type of sealant, the sealant consists of two parts, one containing polymer (also called the base) and a separate component containing the curing agent. These are combined by a mechanical mixer prior to application. Proper mixing is attained in approximately five minutes. Incomplete mixing is indicated by the appearance of streaks in the mix (if the two components are of different colour). At ambient temperatures the pot-life is about three hours. The pot-life decreases with increase in temperature. It is possible to increase or decrease the pot-life by incorporation of an accelerator or a retarder, respectively. At ambient temperatures the sealant cures to form a rubber-like solid.

Polysulphide sealants used for horizontal joints are of a pourable consistency and are referred to as 'pouring-grade sealants'. They have the capacity to flow sufficiently to give a reasonably smooth level surface when applied at ambient temperatures. In the case of vertical building joints, the sealants are made to have a non-sag consistency. These sealants are known as 'gun-grade sealants' and permit application in a suitable joint of any aspect or inclination without appreciable slumping at ambient temperatures.

Reference standards have been adopted for polysulphide sealants in countries such as Australia (Doc. 1572-1970), Canada (19 GP 13a-1970), Japan (JIS-5724-1969) and other countries. However, a good two-component sealant can meet British Standard BS 4254, US Federal Specification TT-S-00227 E and ASTM C-920. Fuel-resistant two-part polysulphide sealants comply with BS 5212-75 and US Federal Specification SS-S-200 D. Sealants used for water retaining and excluding meet the requirement of BS 6920. Polysulphide sealants used for fire protection comply with BS 4254-1983. Additionally these sealants are non-combustible to BS 476, part 4 1984. All these categories will be discussed under separate head-

**Table 7.7** Reference standards for two-component polysulphide sealants

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Scope and standard

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Sealants for general building applications:

US Federal Specification  
TT-S-00227E: 1969  
BS 4254: 1983  
ASTM C-920

Chemical-resistant and fuel-resistant sealants:

SS-S-200 D  
BS 5212: 1975 Dutch Standard KIWA C-50

Sealants for water retaining and excluding structures:

BS 6920: 1988

Intumescent sealants:

BS 4254  
BS-476, Part 4

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ings. Table 7.7 summarises the reference standards for two-component polysulphide sealants.

Polysulphide sealants in general have good adhesion to steel, aluminium and glass, usually without a primer; for porous substrates such as wood and masonry it is recommended to use a primer.

Two-part polysulphide sealants in the cured state have elastoplastic and elastic characteristics. A movement accommodation factor of 25%–30% is possessed by low-modulus sealants and one of 10%–20% by high-modulus sealants. The life expectancy is 20–25 years. They are more suitable for sealing larger joints and also joints that are subject to a somewhat larger degree of movement than are one-component sealants.

In the case of vertical and inclined joints, a shore A hardness of 15–30 is acceptable. Sealants used for pedestrian pavements, or sidewalks, require a minimum hardness of around 25 to withstand pedestrian traffic loads, particularly penetration by stiletto heels. Coal-tar-modified sealants used for airport runways should have a hardness range between 5 and 10. A shore A hardness above 45 makes the modulus higher and reduces the movement capability.

The merits of two-component polysulphide sealants are as follows:

- good flexibility, elasticity, elongation and recovery;
- fast cure;
- better UV resistance;
- resistant to immersed conditions underwater;
- non-staining to masonry;
- excellent resistance for oils and solvents;
- durable for 20–30 years in moving joints;
- better adhesion in peel, and tensile properties.

The demerits are that:

- mixing of components is required;
- the pot-life is limited;
- they have an unpleasant odour;
- they are available in only a limited colour range.

### 7.3.2 *One-component sealants*

These are supplied in ready-mixed form in sealed cartridges, the cure being effected by contact with moisture within the atmosphere. In one-component polysulphides the curing agents are basically metallic oxides. During the manufacture of one-component polysulphide sealants the ingredients should be moisture-free. This is done by carrying the mix in a jacketed kettle under vacuum. The curing agent is added in such a way that it will not immediately polymerise the base. In the final stage, a

blanket of inert gas such as nitrogen is introduced into the mixer in order to avoid the entry of air and moisture. Filling of the cartridges is also carried out under nitrogen.

One-component polysulphide sealants are composed of a blend of polysulphide liquid polymer, plasticisers, fillers, molecular sieves and coated metallic oxides. The function of the molecular sieves is to hold additional catalysts to be released in the curing process and also to attract and hold water to accelerate the curing process (Maslow, 1982). The metallic oxides are generally zinc oxide, zinc peroxide, barium peroxide and calcium peroxide. Curing occurs at room temperature by oxidation accelerated by the absorption of moisture from the atmosphere. A surface skin is formed initially and then the cure rate of the remainder of the sealant depends on the moisture vapour transmission (MVT) rate and the humidity of the atmosphere. The rate of cure is slow, and consideration therefore must be given to the size of joint and joint location. The joint width should not be greater than one inch (2.6 cm) in order to allow the entire mass to cure throughout. Thorough cure normally takes place in three weeks, but with improved technologies it is now possible to achieve a thorough cure in one week.

Owing to their long curing period, one-component polysulphide sealants are not generally used in joints with dynamic movements. When a joint opens and closes under stress and under variations in temperature, a slow-curing sealant may experience cohesive failure as well as deformation.

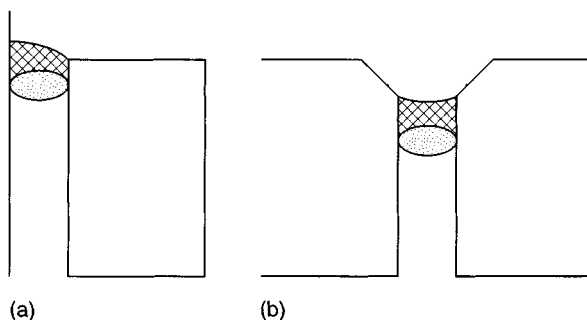
Completely cured one-component polysulphide sealants are elastoplastic and elastic in character. They have a movement accommodation factor of 20%–25%. These types of sealants are particularly suited for the perimeter sealing of window joints [Figure 7.2(a)], joints between precast concrete panels [Figure 7.2(b)], movement joints in brickwork where the movement is likely to be relatively slow, stone claddings, etc. The life expectancy for one-component sealants is, like that of two-component sealants, 20–25 years.

One-component polysulphide sealants comply to British Standard BS 5215, US Federal Specification TT-S-00230 C and Canadian Research Council Standard 19 GP 13a. The merits of one-component polysulphide sealants are as follows:

- there is only one single component, so there is no mixing problem;
- they are ready to use directly from the cartridge;
- they exhibit minimal shrinkage;
- they possess good durability;
- they are available in a range of colours;
- they give good adhesion to most building materials.

The demerits are as follows:

- they require a moderate temperature and high humidity for fast cure;



**Figure 7.2** Use of polysulphide sealant for: (a) perimeter sealing of window joints; (b) in joints between precast concrete slabs. Cross-hatched area = one-part polysulphide sealant; speckled area = support strip

- they have a slow cure rate (1–3 weeks);
- they are not suitable for joints of large width and depth;
- they have low elongation and recovery;
- they are not suitable for pedestrian traffic areas;
- they cannot be applied at temperatures below 4.4°C (40°F);
- they have an obnoxious odour.

## 7.4 End-uses for polysulphide sealants

### 7.4.1 Building and civil engineering applications

Sealants use for these applications are two-component materials in gun and pouring grades. Standard compliance includes: BS 4254; US Federal Specification TT-S-00227 E, type 2, class A; ASTM C 920, type M, class 25. Application involves sealing joints in building and civil engineering structures where movement is expected. They are ideal for expansion joints in reinforced concrete structures such as reservoirs, bridges, seawalls, roads, basements and subways. The pouring version is used for sealing expansion joints and stress-relief joints in floors and other horizontal surfaces.

The cured sealant gives a tough, elastic, rubber-like seal and gives excellent adhesion to concrete and masonry, glass, aluminium and stainless steel. The shore A hardness ranges from 15–35. The movement accommodation factor is 25% in butt joints and 50% in lap joints. These sealants have the capacity to accommodate continuous and pronounced cyclic movements. They are suitable for joints where the joint width may range between 5 mm and 50 mm. Joints which are expected to experience cyclic movements should have a width:depth ratio of 2:1. Minimum sealant depths recommended for different environments are mentioned in Table 7.8. Primers

**Table 7.8** Polysulphide sealants: recommended minimum depths

Joint environment	Minimum sealant depth (mm)
Metals, glass and other impervious surfaces	5
Porous surfaces	10
Joints exposed to traffic and hydrostatic pressure	20

are essential for porous surfaces, glass or glazed surfaces which are to be permanently immersed in water. Other non-porous substrates normally do not require a primer.

Outstanding resistance is offered to weathering, ozone, UV light and attack by chemicals present in industrial atmospheres. These sealants are also used in high-rise buildings where subsequent maintenance is a difficult task. The service temperature for these sealants normally ranges between  $-30^{\circ}\text{C}$  and  $90^{\circ}\text{C}$ .

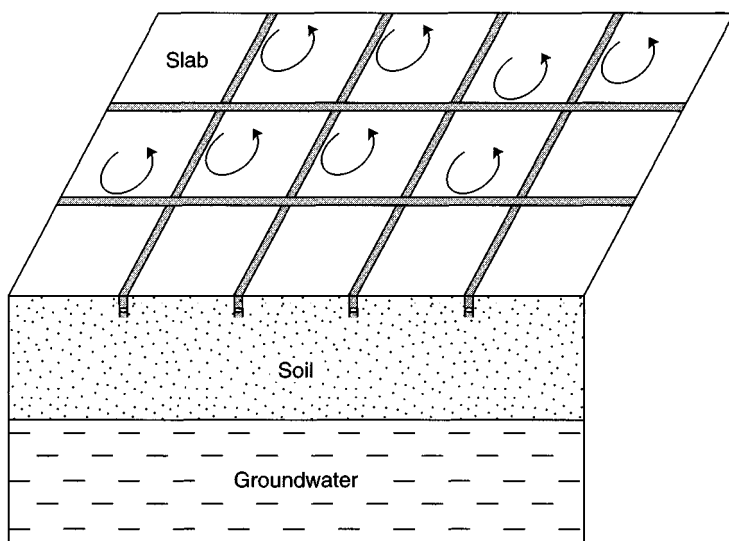
#### 7.4.2 *Protection against environmental conditions*

Polysulphide sealants represent a good technology for environmental protection. Such sealants comply with the requirements of BS 5212 and US Federal Specification SS-S-200 D. They have a high polymer content and low plasticiser content. They possess excellent flexibility and movement tolerance and are resistant to penetration of stones and hard debris. They have prolonged life because of their high age-hardening resistance.

Good resistance to chemicals and hydrocarbon fuels makes these sealants extremely useful in related environments. They have been used for sealing hard-standing areas at airfields where spillages of aircraft fuel and hydraulic fuel occur. Other areas of application subject to fuel and chemical spillage are horizontal movement joints in concrete in the oil industry, refineries, chemical plants, fuel storage areas, and paving associated with motorways, bridge decks, car parks and warehouses.

In the chemical and oil industries slab concrete is widespread in a number of factory environments. These slabs have expansion joints at regular intervals. Such joints when sealed with polysulphide sealants prevent the penetration of liquid into the water-table and thus prevent the contamination of groundwater. Additionally, large chemical plants can have many miles of concrete channels and ducting for services, cables, etc. The same stringent requirements for sealing are applied to prevent permeation of contaminants into the water-table (Lowe, 1994a). Figure 7.3 illustrates the joints in concrete slabs applied with fuel-resistant polysulphide sealant to prevent the spillage of liquids into the groundwater. Tables 7.9 and 7.10 provide data on the chemical resistance of thixotropic and self-levelling polysulphide sealants.





**Figure 7.3** Joints in concrete slabs applied with fuel-resistant polysulphide sealants to prevent contamination of groundwater

### 7.4.3 Petrol stations

This is an important and growing application for chemical-resistant and oil-resistant polysulphide sealants. As a result of a survey commissioned in Germany by the Association for Mineral Oil, Natural Gas and Coal (Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Köhle, 1989, 1991) it was found that less volatile diesel fuels permeate into the ground and contaminate the water-table. It was roughly estimated that one litre of diesel can spoil a million litres of water. The problem is more serious in areas where the water-table is near to the surface.

Sealants used for petrol stations meet the requirements of Dutch Standard KIWA C-50 (KIWA, 1989). The preferred flooring consists of precast concrete hexagonal blocks with a density making them impermeable to fuels. These are laid in a rectangular pattern with a uniform gap between the blocks. Dry sand is blown into the gaps and compacted to an established depth. The concrete is primed followed by application of the sealant. The two important tests for this category of sealants are: resistance to shear where the test piece is subjected to 100 cycles through 100% extension in shear (simulating traffic movement); tests related to end-use which determine tensile adhesion and volume swell after immersion in standard petroleum and diesel fuels at 50°C.

**Table 7.9** Chemical-resistant polysulphide-sealant (specimen according to DIN 52 455, part 1, with acid-resistant clinker): (a) thixotropic; (b) self-levelling. Source: Morton International Ltd, Coventry, UK

Test medium (immersed for 72 h)	Tensile strength (MPa)			Maximum elongation (%)	Adhesion after test	Judgement <sup>a</sup>
	at 50% elongation	at 100% elongation	at cohesion loss			
(a)						
Non-stressed specimen	0.98		0.98	50	OK	
Sulphuric acid						
20%	—		0.75	35	OK	Suitable
40%	—		0.60	30	OK	Suitable
60%	—		0.29	25	OK	Not completely suitable
Acetic acid						
50%	—		0.51	30	OK	Suitable
90%	—		0.41	20	OK	Not completely suitable
Iron(II) sulphate						
10%	—		0.85	45	OK	Suitable
Caustic soda						
20%	—		0.48	25	OK	Suitable
50%	—		0.38	20	OK	Not completely suitable
Sodium hypochlorite						
10%	—		0.69	47	OK	Suitable
<i>n</i> -Octane	0.58		0.80	40	OK	Suitable
Xylene	—		0.54	30	OK	Suitable
Methanol	—		0.40	25	OK	Not completely suitable
Acetone	—		0.26	25	OK	Not completely suitable
Mineral oil	—		0.72	40	OK	Suitable
(b)						
Non-stressed specimen	0.19	0.24	0.33	275	OK	
Sulphuric acid						
20%	0.21	0.26	0.46	420	OK	Suitable
40%	0.15	0.19	0.35	370	OK	Suitable
60%	0.10	0.13	0.14	140	OK	Suitable
Acetic acid						
50%	0.14	0.16	0.33	500	OK	Suitable
90%	0.08	0.10	0.15	556	OK	Not completely suitable
Iron(II) sulphate						
10%	0.13	0.18	0.37	422	OK	Suitable
Caustic soda						
20%	0.14	0.19	0.27	228	OK	Suitable
50%	0.14	0.18	0.20	150	OK	Suitable
Sodium hypochlorite	0.12	0.14	0.27	333	OK	Suitable
<i>n</i> -Octane	0.23	0.29	0.46	375	OK	Suitable
Xylene	0.09	0.12	0.14	167	OK	Suitable
Methanol	0.21	0.27	0.29	156	OK	Suitable
Acetone	0.12	0.14	0.14	90	OK	Suitable
Mineral oil	0.21	0.27	0.51	428	OK	Suitable

<sup>a</sup> The criterion for judgement is the requirement that the results after chemical immersion in the test medium must show a minimum of 50% of the original properties. Not completely suitable means that the results after immersion are on the borderline of the requirement.

**Table 7.10** Chemical-resistant polysulphide sealant tested according to DIN 53521; (a) thixotropic; (b) self-levelling. Source: Morton International Ltd, Coventry, UK

Test medium (immersed for 72 h at 23°C)	Volume change (%)	Mass change (%)	Volume change after drying (%)
<b>(a)</b>			
Sulphuric acid			
20%	-1.7	-4.0	-2.7
40%	-1.3	-0.2	-2.8
60%	-	-	-
Acetic acid			
50%	41.8	53.8	-1.3
90%	54.6	69.5	-8.2
Iron(II) sulphate			
10%	2.6	2.5	-2.1
Caustic soda			
20%	1.0	1.7	-1.9
50%	0.8	0.8	-1.6
Sodium hypochlorite			
10%	-	-	-
<i>n</i> -Octane	-3.2	-3.9	-5.1
Xylene	26.6	43.7	-10.8
Methanol	0.9	4.8	-7.8
Acetone	15.9	31.0	-11.5
Mineral oil	-2.9	-4.7	-4.0
<b>(b)</b>			
Sulphuric acid			
20%	-0.7	-1.1	-2.3
40%	-1.8	-3.7	-
60%	-	-	-
Acetic acid			
50%	14.8	14.4	-3.0
90%	20.7	33.0	-24.7
Iron(II) sulphate			
10%	-0.3	-0.9	-3.0
Caustic soda			
20%	0.0	-0.8	-2.7
50%	0.1	-0.2	-2.4
Sodium hypochlorite			
10%	-	-	-
<i>n</i> -Octane	-7.9	-7.6	-10.4
Xylene	-9.0	7.2	-48.9
Methanol	-12.2	-9.7	-20.8
Acetone	-30.7	-18.9	-54.2
Mineral oil	-5.5	-6.5	-8.2

It is estimated that about 1200 petrol stations have been sealed with this technology in Holland. In Germany 500 petrol stations were sealed in this way in 1994 and the rest were committed to completion by 1996 (Lowe, 1994a).

Good housekeeping is mandatory to maintain the durability of these sealants. This can be done by daily washing the surface and channelling the washings into separators for disposal.

#### 7.4.4 *The water industry*

Difficult environments for sealant materials are long-term immersion in water or continuous exposure to high humidity. A sealant immersed in water or exposed to saturated water vapour will be subject to physical, chemical and biochemical changes. The useful life of a sealant will depend on the relative levels of these effects, which in turn will depend on the type of polymer used and the formulation. The changes may occur in bulk or on the surface, and may lead to a loss of adhesion, which is the most damaging result of attack by water (Lee *et al.*, 1992).

Bacterial attack and fungal growth are the two biochemical effects which influence the durability of a sealant. Bacterial attack results in the chemical breakdown of the sealant. Fungi attach themselves to the surface of the sealant and live as parasites, feeding on the organic matter present. The use of polysulphide sealants in the water industry has proved to be a versatile method for overcoming the above-mentioned problems.

This important aspect of polysulphide polymers is spearheading the protection of groundwater and the surrounding environment. It is used in water-retaining and water-excluding structures both for potable water and for waste-water. The main application areas are water reservoirs, irrigation canals, sewage storage and treatment tanks. Application with either type of water utilises the bio-resistance and excellent ageing properties of polysulphide polymers.

Such materials in contact with potable water must be non-toxic and non-tainting. Water-industry sealants contain a high percentage of polysulphide polymer (minimum 40% by weight). The curing system is manganese dioxide. These sealants comply to BS 6920 and to Water Industry Specification WIS 4-60-01 (Lowe, 1994b). Compliance to the Drinking Water Inspectorate's (DWI) requirement under clause 25(1)b of the water-supply regulations 1989 is also met by many sealants.

Water-industry sealants have a fast cure rate and the ability to accept early cyclic movement, even at low temperatures. They provide long-term performance under permanently immersed conditions and are resistant to anaerobic bacteriological conditions associated with sewage.

Water-industry sealants are selected on the basis of the movement accommodation factor and long-term performance. Depending on the

structure type, they need to cope in the long-term with one or more of the following:

- hydrostatic pressure;
- cyclic movement;
- immersion;
- aggressive chemical or biological attack.

The movement accommodation factor is the same as that of the other two-component polysulphide sealants (i.e. 25% in butt joints and 50% in lap joints). A five-year study has been carried out at Finham Sewage Plant, Coventry, UK, on the bioresistance of such polysulphide sealants by immersing the sealants in highly bioactive water found under conditions of heavy silting and deoxygenation. The objective of the study was to determine the compound constituents which will enable these sealants to meet the new, more demanding, tests for sealants, to have true long-term resistance to clean or dirty water and to give reliable performance in applications where high humidity may prevail (KIWA, 1989). It was established that the compound formulation has an influence on the ability of the sealant to resist bacterial attack. The conclusions from the study were as follows:

- manganese-dioxide-cured sealants are more resistant to biodegradation than are lead-dioxide-cured sealants;
- the higher the polymer content of the sealant the more resistant it is to biodegradation;
- certain biocides further increase the resistance to biodegradation of manganese-dioxide-cured sealants;
- it is possible to further increase bioresistance by correct choice of fillers and plasticisers.

Observation of sealants after eight years has shown that an additional three years' immersion had no effect on the sealant (Morton International, 1992). These samples were finally removed from Finham Sewage Plant after 10 years' immersion with no observable change having occurred in the eight-to-ten-year time period (personal communication, 19 August 1996, Ray Robinson, Morton International, Coventry, UK). The sealants with the best resistance to bacteria had the lowest volume swell and the most durable adhesion to primed concrete (KIWA, 1989).

The long-term testing of specialised polysulphide sealants in the sewage environment has led to formulations not only for that environment but for universal applications in water, whether contaminated, clean or for potable use.

#### *7.4.5 Fire protection*

This technology of polysulphides offers fire protection in building structures and fulfils stringent regulations for minimising the risk of fire. Under

normal conditions they perform as effective building sealants, under conditions of fire they intumesce, expanding to form a closed-cell foam-like structure which insulates and provides a barrier to hot gases and flames.

Intumescent sealants are widely used in expansion and compression joints, construction gaps, fire protection panels, fire doors and around cable and pipe penetration. They work with, or replace, fire stops and preformed seals in the creation of compartments which are essential to efficient fire protection.

Owing to recognised performance under fire conditions, intumescent sealants can be used to maintain the continuity of fire rated walls, floors and ceilings, confirming smoke and fire and giving extra time for people to escape (Jackson, 1992).

Intumescent sealants usually have 25% movement capability. They meet the relevant performance requirements of BS 4254 and pass the fire testing programme in accordance with BS 476, part 20-1987.

## **7.5 Polysulphide coatings**

These represent a versatile technology that contributes to the fields of environmental protection and pollution control. This technology is the result of legislation in many countries requiring the control of spillage of secondary containments above or below ground. These are made of concrete or brick walls, built on concrete floors. With these structures there is a possibility of deterioration or development of cracks as time passes. It has been found that treating the surface with a polysulphide coating is an effective way to make the containment viable. Such coatings contain liquid polysulphide polymers with reinforcing carbon black cured with manganese dioxide. The presence of carbon black makes the coating more durable by providing toughness and UV stability. No signs of deterioration were found after 10 000 h under an 800 W tungsten UV lamp (Lowe, 1994a). These coatings are flexible with a crack-bridging capability over a period of many years. Other characteristics include exceptional resistance to oils, fuels and solvents, low permeability to gases and vapours, high resistance to ozone and UV, low-temperature resistance to  $-45^{\circ}\text{C}$  without plasticisation and a high level of toughness. All these properties make the coating a good choice for use in conditions of constant outdoor exposure.

The coating is two-component and needs mixing on-site prior to application. It can be applied either using conventional airless spray equipment or by brush or roller. A final thickness of 1 mm to 2 mm can be obtained with two coats. Pretreatment of the substrate with an epoxy primer ensures good adhesion. Defects in the concrete or brickwork are sealed with an elastomeric sealant which is resistant to the fluid being stored in the tank.

The coating can cure in two hours to form a seamless elastomeric membrane. In order for the coating to get approval for use with potable water it must pass a series of tests, including tests concerning depletion of dissolved oxygen, extraction of toxins and heavy metals and tainting. The technology of polysulphide coatings is used to fulfil a wide range of applications in the areas of environmental and pollution control (Harris, 1989). Some of the more important applications are as follows:

- linings
  - chemical plants,
  - water-treatment plants [Figure 7.4(a)],
  - effluent tanks,
  - bund-retaining walls,
  - silage clamps,
  - storage tanks for fuels, oils, liquefied petroleum gas, etc.;
- construction
  - bridge-deck membranes,
  - membranes for storage tanks and retaining walls,
  - in-place gaskets for preformed concrete panels, pipes, etc.,
  - spillage-resistant roofing systems [Figure 7.4(b)].

The properties of polysulphide coatings are given in Table 7.11. A volume swell of less than 150% after 72 h is acceptable (Lowe, 1994a).

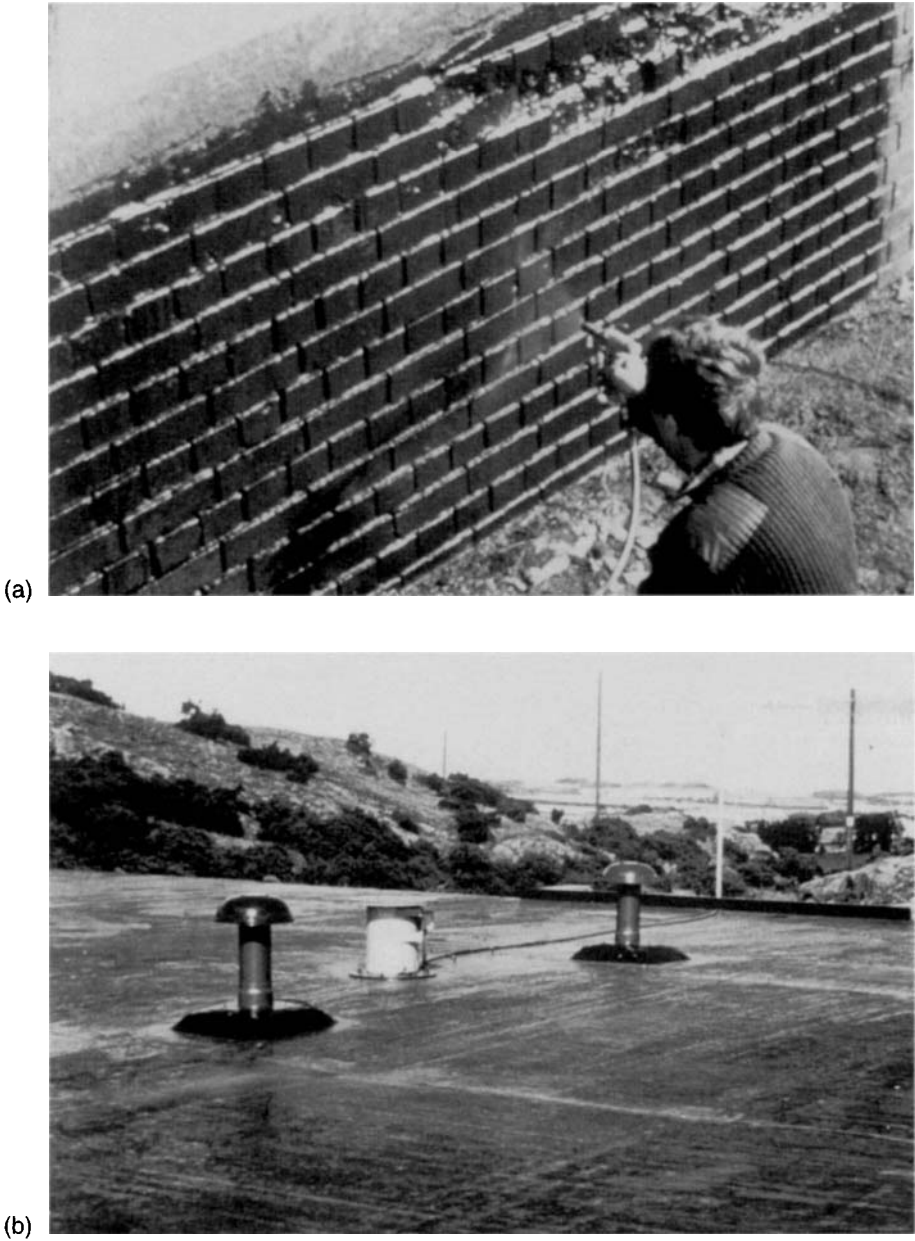
## 7.6 Health and safety

Generally, polysulphide polymers are regarded as safe. They are odoriferous because of presence of sulphur. Acute inhalation studies have shown these polymers to be non-toxic. However, the low molecular weight polymers such as LP-3 and LP-33 are skin soluble and require care in handling.

Thermal degradation studies of polysulphide sealants have shown the evolution of gases such as hydrogen sulphide, ethylene, sulphur dioxide and carbon dioxide, but the rate of evolution of these compounds was found to be below the level considered hazardous (Berenbaum, 1969).

A few of the compounding ingredients can be harmful. Lead dioxide curing agent is toxic and can lead to lead poisoning if ingested. Some formulations of one-component sealants contain barium oxide as a dehydrating agent. Such sealant cartridges should be marked as toxic. Phenolic resins and epoxy primers may give rise to allergic reactions if not handled properly (Panek and Cook, 1984).

During 1995, Morton International reviewed the ecotoxicological data on the LP<sup>®</sup> liquid polysulphide polymers. These data have resulted in the



**Figure 7.4** Applications for polysulphide coatings: (a) filter bed; (b) reservoir roof.  
Reproduced with permission from Morton International Ltd, Coventry, UK



**Table 7.11** Properties of polysulphide coatings. Source: Morton International Ltd, Coventry, UK

Property	Value
Hardness (shore A)	41
Tensile strength (MPa)	2.5
Elongation at break (%)	490
Permeability to gasoline (cm/s)	$1.23 \times 10^9$
Volume swell after 72 h immersion at 23°C (%):	
ASTM fuel D	15
Methanol	0.6
Toluene	120
MEK (methylethylketone)	62
Ethyl acetate	42

polysulphide polymers being classified as R51/53, 'toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment', with the 'N' symbol (Rees, 1996). In the USA Morton have carried out five further ecotoxicological studies in three freshwater and two marine aquatic species with the aim of establishing a more accurate classification. The highest toxicity was seen in freshwater algae. From these results the classification of the LP<sup>®</sup> liquid polysulphide polymers would be R52/53, 'harmful to aquatic organisms, may cause long-term adverse effects in the aquatic environment', with no symbol (Rees, 1996).

It is advisable to handle polysulphide polymers in adequately ventilated environments because under conditions of intensive exposure they may cause nasal irritation. As a precautionary measure protective gloves based on nitrile or latex rubber should be used and repeated contact with the skin should be avoided. The use of safety goggles and face shields is also recommended.

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## 8 Alkyds in the construction industry

### 8.1 Alkyd coatings

More than 95% of the alkyds are used for coating applications. Owing to their good wetting and dispersing properties, alkyds are ideal vehicles for pigmented coatings. For years they have been used as protective as well as decorative coatings. They are a most versatile material for wood and metals, especially iron and steel. The most common application of alkyd coatings is for wooden and steel doors, windows, grills, etc. The properties that make alkyd coating so popular are (Blegen and Fuller, 1967; Holmberg, 1987; Oldring, 1987):

- low cost;
- excellent durability;
- excellent gloss and gloss retention;
- flexibility;
- toughness;
- weathering resistance;
- solvent resistance;
- resistance to saltbrine and mineral oils;
- suitable for exterior and interior areas.

Owing to wide variations in composition, alkyd coatings vary widely in performance during application, service and also in cost. Selection of alkyd coatings thus depends upon:

- performance during application by methods such as spraying, dipping and brushing;
- performance in service in terms of flexibility, abrasion and scuff resistance, resistance to corrosion, acid, alkali, grease, gasoline and heat stability;
- cost performance level.

Alkyd coatings are available in both clear and pigmented form. These coatings protect and decorate a wide variety of substrates. The type and amount of oil or fatty acid in the alkyds determines to a large extent their end-use application and have an important effect on properties such as drying speed, gloss and gloss retention, colour retention, adhesion, flexibility, hardness, mar-proofness, and gasoline and water resistance (Allied

Chemical, 1958; Patton, 1962; Payne, 1965). The properties of alkyd coatings are given in Table 8.1.

Alkyd coatings are widely used for wood and steel substrates (Figure 8.1). Pure alkyd coatings when applied on concrete and masonry have the danger of oil saponification. However, modified alkyds can be used on concrete substrates without too much risk.

When formulated with suitable pigments, alkyd coatings can be used to impart anticorrosive properties. Alkyd coatings are also used as cosmetic topcoats with other types of coatings; for example in marine environments epoxy coatings are applied to fulfil a protective function, following by application of alkyd topcoat to prevent chalking of the epoxy coating (Bleile, 1989).

**Table 8.1** Properties of alkyd coatings

Property	Description
Resin composition	Polyacid, polyalcohol, drying oil
Curing mechanism	Solvent evaporation, oxygen adsorption
Solvents and thinners	Mineral spirit, turpentine
Suitable substrates	Wood, steel
Outstanding properties	Gloss retention, durability, weatherability
Atmospheric exposure	Industrial and humid atmospheres
Immersion service	Not used
Service not recommended	Exposure to chemical fumes



**Figure 8.1** Portacabins painted with alkyd coating

Alkyd coatings are not recommended for immersion service or for use in areas which are routinely subject to accidental immersion.

## 8.2 Health and safety

During the manufacture and processing of alkyds, stringent safety practices should be maintained. Many solvents are hazardous and have low flashpoints. Adequate ventilation minimises fire and toxic hazards. Use of rubber gloves, protective clothing, eye protection and respiratory devices is recommended when handling ingredients as well as finished coatings.

Application of coatings should also be made in ventilated areas. If the coating comes into contact with the skin, do not use a solvent for cleaning purposes. Remove the coating with a piece of clean cloth, followed by cleaning with soap and water. In case of eye contact flush continuously with clean water for 10–15 minutes. Emergency cases should be referred immediately to a physician.

Safety regulations should be enforced and accident-prevention programmes should be conducted to develop awareness among employees.

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## 9 Polyesters in the construction industry

### 9.1 Introduction

Technologies offered by unsaturated polyesters to the construction industry are directed at specific areas such as anchoring grouts, resin mortars and concretes, coatings and lighting sealants. The properties that make unsaturated polyesters more useful for construction are (Boeing, 1964; Demmler and Schlag, 1971; Manson, 1985):

- rapid strength gain;
- excellent abrasion resistance;
- chemical resistance;
- corrosion resistance;
- heat resistance;
- high impact strength;
- excellent compressive strength.

Table 9.1 highlights the properties, products and applications of unsaturated polyesters.

### 9.2 Properties

The properties of cured polyesters are affected by their structural elements. These elements include the structure and ratio of acids and glycols, the type of end-group present, the type of unsaturation and the distribution of various repeating units.

#### 9.2.1 Hardness

Glycols with fewer ether linkages have increased hardness, and an increase in the content of propylene glycol increases the hardness. Aromatic acids impart more hardness, whereas aliphatic acids with long chains lower the hardness.

#### 9.2.2 Tensile and flexural strength

The chemical structure of glycols influences the tensile and flexural properties of cured polyester resins. Glycols with more carbon atoms generally

**Table 9.1** Properties and application areas of polyester systems in the construction industry

Product and property	Application
Anchoring grout: controllable setting time rapid strength gain corrosion resistance	Securing bolts, bars, tendons or dowels in drilled or formed holes in concrete masonry or natural rock
Coatings: resistance to mineral acids resistance to a wide range of pH biological resistance	Tank linings Sewage-treatment plants
Concretes and mortars: rapid cure early, high compressive strength even at low temperatures	Galvanic protection of bridge decks Filling cable slots Areas where rapid cure and early strength are required
Loop and lighting sealants: excellent adhesion to concrete, asphalt and steel in dry or damp conditions without primer resistance to de-icing salts and hydrocarbons	Sealing horizontal cable slots in concrete and asphalt pavement Bedding and sealing around airport lighting units

give higher values of tensile strength, and the flexural properties of phthalate-fumarate resins are greater with diethylene glycol as compared with propylene glycol.

### 9.2.3 Heat distortion temperature

The heat distortion temperature (HDT) is a function of the cross-link density and depends upon the type of glycol. In the case of propylene and diethylene glycol, the HDT becomes smaller at higher levels of unsaturation.

### 9.2.4 Impact strength

Polyesters containing long-chain unbranched glycols have the highest impact strength. This property also increases with the increase in the chain length of aliphatic acids.

### 9.2.5 Water absorption

Water absorption is less in the case of cured polyesters containing aromatic acids, compared with those containing aliphatic saturated acids. Factors that contribute towards the flexibility of cured polyesters also tend to promote water absorption. The water sensitivity of cured resins also depends on the relative amounts of terminal hydroxyl and terminal carboxyl groups.

### 9.2.6 *Hardness*

The presence of unsaturated acids with shorter chains gives greater hardness to the cured system. Longer-chain aliphatic acids lower the hardness.

### 9.2.7 *Compressive strength*

The type of acid present in the polyester influences the compressive strength. Polyesters based on aliphatic saturated acids have a low compressive strength.

### 9.2.8 *Heat resistance*

The vinyl portion of the polyester is responsible for heat deterioration. The less the degree of unsaturation, the better the heat resistance.

With continuous ageing, degradation of the cross-links occurs resulting in loss of flexural strength in the cured polyester. Use of proper antioxidants improves the resistance to heat deterioration.

### 9.2.9 *Abrasion resistance*

Resins containing a high degree of unsaturation provide excellent abrasion resistance.

### 9.2.10 *Chemical resistance*

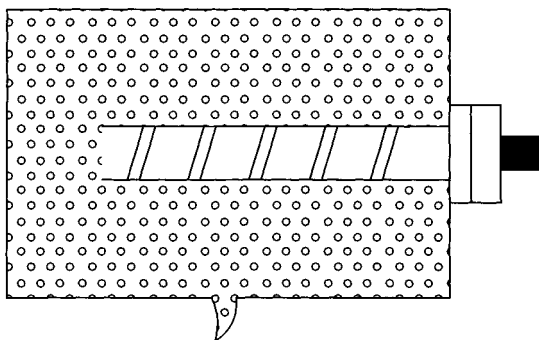
Long-term exposure to a number of different chemicals reveals that isophthalic polyesters give products with a higher chemical resistance compared with phthalic polymers. Use of hydrogenated bisphenol A as the glycol component offers additional improvement to the compressive strength (Boeing, 1969).

## 9.3 **Anchoring grouts**

Polyester anchoring grouts are used mainly for securing bolts, bars, tendons or dowels in drilled or formed holes in concrete, masonry or natural rock. They are particularly suitable where rapid installation and rapid strength gain are required. They are also used in areas where a high degree of corrosion protection is needed.

Distinct areas of application are for rock bolting (Figure 9.1) and for load-bearing anchorages (Figure 9.2). In rock bolting the anchored unit reinforces and supports natural rock against its own movement (e.g. tunnels, cliff faces). In load-bearing anchorages, external loads are





**Figure 9.1** Scheme of a bolt grouted in a polyester anchor



**Figure 9.2** Sample showing a bolt in a polyester anchorage system. Reproduced with permission from Fosroc

sustained and transferred to the solid material in which they are anchored (e.g. attachment of machinery, equipment, structures, etc. against movement (Fosroc International, undated a).

Polyester anchoring grouts are supplied in two components, consisting of measured quantities of resin base and catalysed filler. The two components are mixed before application.

Polyester anchoring grouts are of two types: pourable grouts and thixotropic grouts. Pourable products are designed for vertically downwards or declining anchor holes prior to insertion of the anchor unit. The

thixotropic version is suitable for horizontal or inclined holes. They are injected with the aid of a simple hand piston pump, the barrel of the pump being inserted into the extremity of the hole and the resin injected while the pump is slowly withdrawn.

The advantages of polyester anchoring grouts are as follows:

- reaction and setting time can be controlled, from a few seconds to several hours;
- rapid strength gain;
- tolerant to temperature (can react from 0°C);
- as claimed by most manufacturers, the product is water-tolerant and will cure under water;
- resistance to corrosion;
- low costs compared with epoxies.

The disadvantages are:

- compared with their epoxy counterpart, shrinkage occurs during the cure;
- chemical resistance is low compared with epoxy grouts;

Specific areas of application for polyester anchoring grouts are (Fosroc International, undated a):

- sewerage, drainage, water and telephone installations where the attachment of ladders, brackets, cables, etc. to concrete is required under highly corrosive conditions;
- ground anchoring of television and radio masts and electricity transmission towers on rock bases;
- fixing of crane rail and equipment bolts, quayside fender bolts, and anchoring of lock seal bolts.

## 9.4 Polyester coatings

Polyester coatings are suitable for concrete and steel substrates. The systems are generally used as laminates in conjunction with the use of glass cloth or glass flakes as the reinforcement. Polyester coatings are particularly useful in areas where resistance to mineral acids is required. Typical properties of polyester coatings are given in Table 9.2.

Polyester coatings can be formulated as solvent-based as well as 100% solid coatings. In order to provide a non-sagging effect, proper selection of fillers is essential. Systems based on the reaction between maleic anhydride and bisphenol A offer greater chemical resistance over a wider range of pH.

Water inhibits the cure of polyesters, therefore it is essential to apply a moisture-insensitive primer to the concrete before applying a polyester

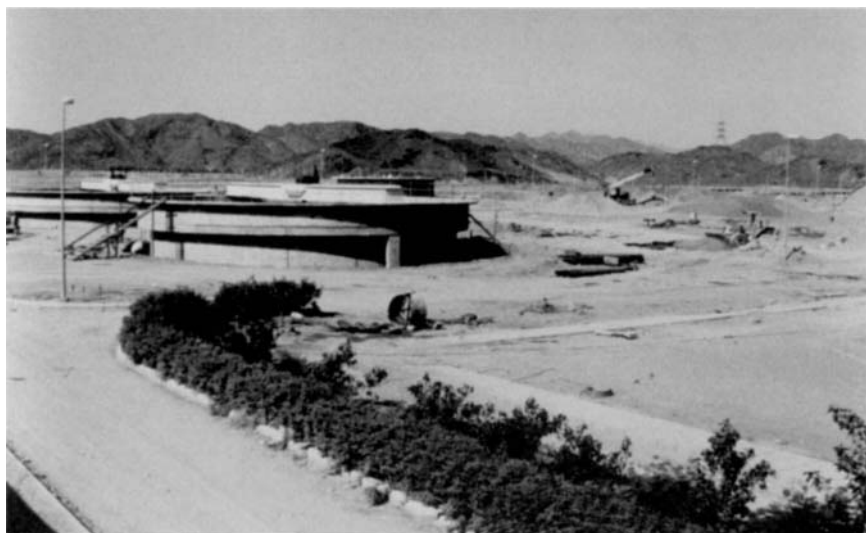
**Table 9.2** Typical properties of polyester coatings

Property	Description
Resin composition	Organic acid, polyalcohol, styrene
Curing mechanism	Polymerisation
Solvents (if used)	Ketones
Suitable substrates	Concrete, steel
Priming	Essential
Outstanding properties	Resistance to acids and solvents
Atmospheric exposure	Humid atmospheres
Immersion service	In water, acids, crude oil
Service not recommended	Alkali immersion

coating. Air is another factor that inhibits the cure of some polyesters. This problem can be solved by applying a final topcoat that contains about 1%–2% paraffin. The paraffin rises to the surface and prevents direct contact between the polyester surface and air; topcoats without paraffin may result in a tacky surface (ACI, 1985).

Polyester coatings find application in tank linings and floors. In both cases, the systems are generally used as laminates. Owing to the resistance over a wide range of pH they do well in effluent trenches and buffer tanks (Figure 9.3).

Polyester coatings have been used in renovation work carried out to the preconcentrator at the Heidelberg South Sewage Treatment Plant, to repair pipeline systems and the main large sewers and shafts which



**Figure 9.3** A sewage treatment plant where polyester coating has been applied to interior surfaces

were damaged by the high concentration of waste in aqueous effluents (Schik, 1993).

Advantages of glass-fibre-reinforced polyester coatings are:

- resistance to chemicals and to substances formed by biological processes;
- resistance to temperature fluctuations;
- good shape retention and mechanical strength;
- resistance to a wide range of pH.

## 9.5 Polyester concretes

Polyester concretes are used as a repair material in a similar fashion to epoxy mortars. They are also two-component systems. The material has a pot-life of usually 45 minutes at ambient temperatures but it is possible to adjust the pot-life by controlling the amount of catalyst. Formulators market the product in winter and summer grades.

Owing to this rapid cure, a compressive strength of 40 N/mm<sup>2</sup> is possible within 2 h at temperatures down to 4°C (Shaw, 1993a). The properties of polyester binder depend primarily upon the chemical composition of the polyester resin component. Typical physical properties of cured polyester binders for concrete overlays are given in Table 9.3 (ACI, 1993).

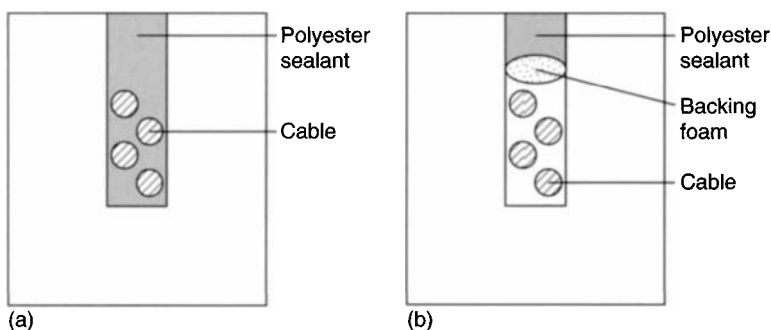
Polyester concrete overlays are applied to bridge decks to protect against galvanic corrosion of the reinforcement and subsequent cracking and spalling of the concrete (O'Connor and Saiidi, 1993). Polyester resin mortars and concretes with aggregate:binder ratios up to 11:1 by weight have been used for more than 20 years for airport runway repairs and for the installation of runway lights and similar applications where their rapid strength-gain properties are essential (Shaw, 1993b).

Low modulus polyester resin mortars have also been developed. They too cure rapidly. They are principally used to fill cable slots cut across asphalt runways and also to fill over PVC cable ducts installed in concrete runways and taxiways (Shaw, 1993b).

Thermal contraction and volume shrinkage during the cure are the disadvantage of polyester systems.

**Table 9.3** Typical physical properties of cured polyester concrete

Property	Value	Test method
Bond strength (MPa)	7	ASTM C 882
Coefficient of thermal expansion (mm/mm/°C)	$36 \times 10^{-5}$ – $90 \times 10^{-5}$	ASTM D 696
Tensile strength (MPa)	14	ASTM D 638
Curing shrinkage (%)	1–3	ASTM D 955



**Figure 9.4** Sawn cable slot: (a) no movement; (b) movement joint

## 9.6 Polyester loop and lighting sealants

These are two-component materials used for sealing horizontal cable slots (Figure 9.4) in concrete and asphalt pavements, associated with road traffic signal controllers and inductance loops, airport runway lighting and automatic barriers or gates. They are also suitable for bedding and sealing around airport lighting units (Figure 9.5) (Fosroc International, undated b).

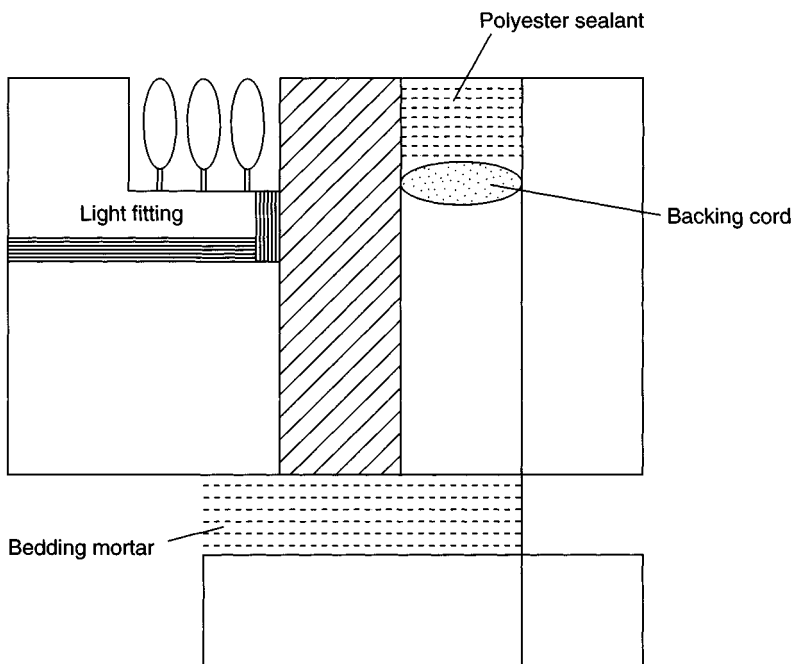
Polyester lighting sealants are self-levelling materials suitable for pouring into horizontal slots. They cure to form a tough resilient seal with a limited degree of movement. Salient features of polyester lighting sealants are as follows:

- excellent, primerless, adhesion in dry or damp conditions to concrete, asphalt and steel;
- resistance to chemicals, de-icing salts and hydrocarbons;
- fast curing – can be applied and cured below freezing point;
- slight flexibility to accommodate limited movement.

In the case of sawn cable grooves without any movement, the cables are totally sealed and encapsulated with the sealant [Figure 9.4(a)]. Where movements are anticipated in the sawn joints, cables should be laid free at the base [Figure 9.4(b)]. A closed-cell polyethylene cord should be located above the cables, followed by sealing of the joint, as shown in Figure 9.4(b).

## 9.7 Health and safety

Health and safety problems associated with polyester resins are related to styrene and its emission into the environment during mixing, application and curing. Inhalation and skin absorption are the main routes of



**Figure 9.5** Bedding and perimeter seal light fitting

exposure. Styrene is an irritant to the eyes and mucous membranes and is a depressant to the central nervous system (Makhlouf, 1982).

The hazards pertaining to compounding are related mainly to the storage and handling of promoters and accelerators and the use of flammable solvents for clean-up.

As a part of the safety routine, gloves and barrier creams should be used when handling polyester products. Skin contact should be avoided. In case of accidental contact with skin, immediate washing with soap and water should be practised. Never use solvent for cleaning polyester spillages on the skin. Wash any eye contamination with plenty of water and seek medical advice immediately. Good ventilation is necessary during working.

Polyester resin and initiator components should both be stored in cool, protected areas.

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## **10 Hybrid polymers**

### **10.1 Introduction**

Hybrid systems are combinations of two different types of polymers in the form of a cold mix or precondensate. These combinations unite certain properties of both components which could not be obtained in a single polymer alone (e.g. epoxy-resin-based compounds have many excellent properties including rapid curing at normal temperatures, good adhesion to most surfaces, toughness and chemical resistance to many dilute acids, alkalis and solvents). The incorporation of a polysulphide component into an epoxy resin leads to the improvement of certain properties without adversely affecting the existing performance capabilities of the epoxy system (Rees *et al.*, 1994). The benefits from such modifications include viscosity reduction, enhancement of adhesion, introduction of flexibility, improved impact strength, thermal shock resistance, improved water and corrosion resistance, controlled damping characteristics and improved chemical resistance (Rees and Wilford, 1994).

Several other polymers such as polyurethanes, alkyds, acrylics, polyesters, silicones, etc. can be hybridised to improve the performance or to obtain desired end-results. The growth of hybrid polymer technology is giving rise to considerable improvements, and many hybrid systems have been introduced to the market. Most of the work reported in this field is for coatings, but at the same time it is useful for other products used in the construction industry. Research is under way by many polymer manufacturers and universities, and innovations are continuously being reported. In this chapter we shall be dealing with those combinations which are useful, or may be useful, for the construction industry.

### **10.2 Epoxy-polysulphides**

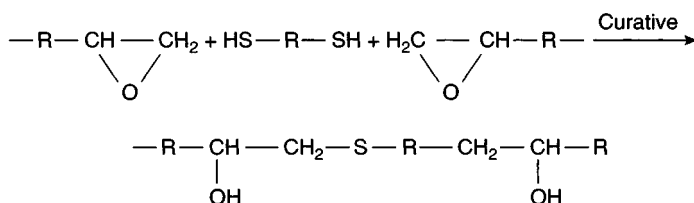
The beneficial properties of polysulphides and epoxies can be combined to impart a synergistic effect to the system. Individual details of the polymers have been discussed in Chapters 3 and 7. The advantages of incorporating a liquid polysulphide (LP) polymer into an epoxy resin have already been highlighted (section 10.1). Of these, the development



of flexibility has historically received the greatest emphasis in the marketing of these polymers as epoxy modifiers.

The lower molecular weight LP-3, LP-33 and ZL-1400 C polymers are used as elastomeric modifiers, particularly for epoxy coatings and adhesives. Owing to their low molecular weight these polymers have the lowest viscosities of commercially available LPs. This low viscosity is particularly beneficial under cold conditions. Even at 4°C the polymers have viscosities which are considerably lower than those associated with standard unmodified bisphenol A [diglycidyl ether of bisphenol A (DGEBA)] epoxy resins at 25°C.

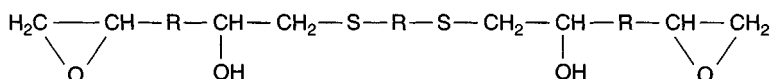
LP-modified epoxy resins are manufactured by reacting two moles of an epoxy resin with one mole of liquid polysulphide:



Cured epoxy – polysulphide resin

The reaction is catalysed by an organic base, usually an amine, which in the past has nearly always been the tertiary amine 2,4,6-tri(dimethyl aminomethyl) phenol. Such LP-modified epoxy resins have been in existence for more than 30 years. Their popularity declined because of the mercaptan odour of the polysulphide polymers in the uncured state and because of the use of a tertiary aromatic amine.

Another development that has triggered the revival of liquid polysulphides as modifiers for epoxy resins has been the introduction of polysulphide–epoxy prepolymer compositions which have no mercaptan odour in the uncured state. The manufacture of such compositions involves the co-reaction of epoxy resin in molar excess with a suitable liquid polysulphide in the absence of a catalyst to give:



The resulting stable prepolymers or adducts are end-capped with oxirane groups, which can be cured with any of the following hardeners (Rees *et al.*, 1994):

- liquid aliphatic amines;
- liquid cycloaliphatic amines;

- liquid aromatic amines;
- liquid polyamides;
- solid isolated amine adducts.

The amount of curative used with an adduct system is calculated from the epoxide equivalent weight of the adduct and the hydrogen equivalent weight of the curative.

Adducts can be manufactured from either liquid or solid epoxy resins by using whatever level of LP is appropriate for the properties required for the cured product. The only limitation is that a molar excess of epoxy resin must always be maintained (Rees *et al.*, 1994; Morton International, undated a). Properties of epoxy-polysulphide adducts manufactured by the above route include (Morton International, undated a):

- excellent adhesion to many substrates, such as oily and rusty steel;
- improved durability in corrosive or high-humidity environments;
- flexibility and impact resistance;
- chemical resistance to a wide variety of fluids, particularly fuels and oils;
- can be formulated as single-component (high-temperature cure) or two-component (ambient cure) systems.

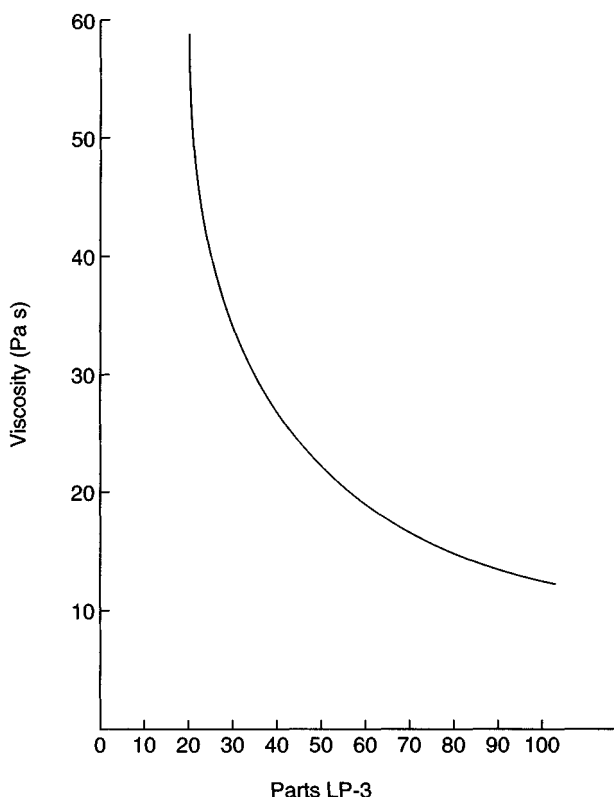
It is possible to make tougher products if the level of liquid polysulphide used in the manufacture of a conventional LP-epoxy resin lies in the range of 15–65 pph of epoxy resin (Rees *et al.*, 1994).

The practice of modifying epoxy resins with liquid polysulphides may not be new but the method of doing so has advanced significantly in recent years to the extent that these systems are being given serious consideration in the design of specialist coatings, primers, adhesives and encapsulants (Morton International, undated a; Rees and Wilford, 1994; Rees *et al.*, 1994).

Epoxy-polysulphide adducts or prepolymers are commercially available under the trade name ELP (a trade mark of Morton International). Properties of one such adduct, ELP-3 are presented in Table 10.1.

**Table 10.1** Properties of commercial epoxy-polysulphide polymer ELP-3® (Morton International). Source: Morton International Ltd, Coventry, UK

Property	Typical value or description
Physical state	Clear amber liquid
Odour	Sweet
Viscosity at 25°C (Pa s)	2.0–2.8
Specific gravity at 25°C	1.27
Molecular weight (average)	1000
Epoxy equivalent weight (g/mol)	600–750



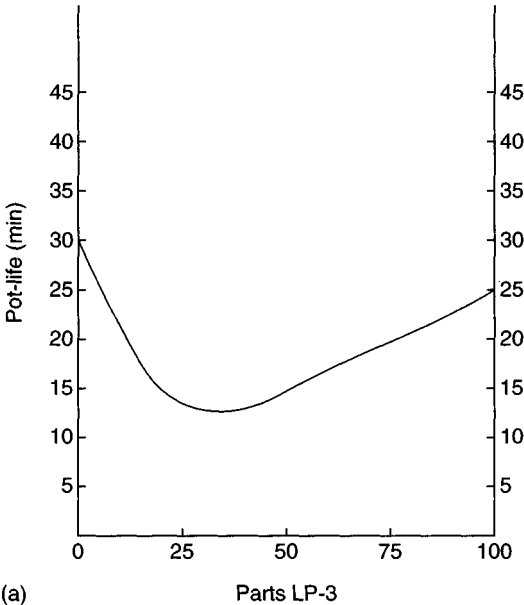
**Figure 10.1** The addition of LP-3 to a diglycidyl ether of bisphenol A (DGEBA) resin: viscosity at 5°C as a function of parts LP-3 per 100 parts of epoxy resin. Redrawn with permission from Morton International Ltd, Coventry, UK

### 10.2.1 Properties of epoxy-polysulphide hybrids

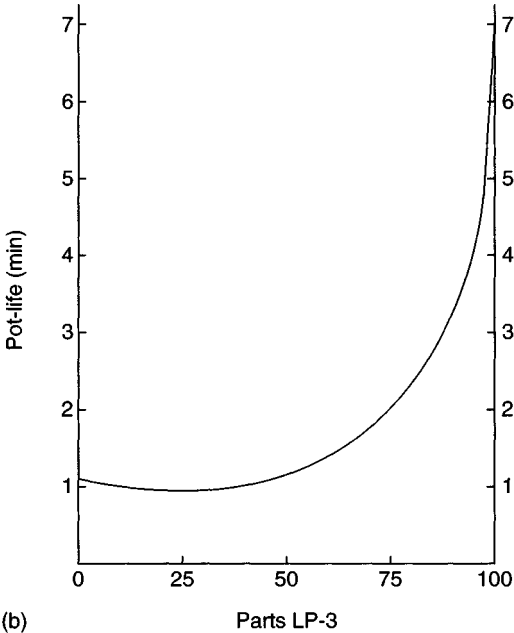
**10.2.1.1 Viscosity.** Modified polymers exhibit lower viscosity, which is particularly useful at lower service temperatures. The lower mix viscosity enables LP-epoxy resins to be readily formulated into solventless or high-solids coatings (Figure 10.1).

**10.2.1.2 Curing properties.** Depending on the level of LP used and on the reactivity of the curative, it is possible to accelerate or retard the rate of cure of an epoxy-amine system (Figure 10.2).

**10.2.1.3 Adhesion.** Owing to improved wetting properties, excellent adhesive characteristics are exhibited for coatings and adhesives with relatively small additions of liquid. Polysulphides are required to produce significant improvements in the lap shear strength of the system (Rees *et al.*, 1994).



(a)



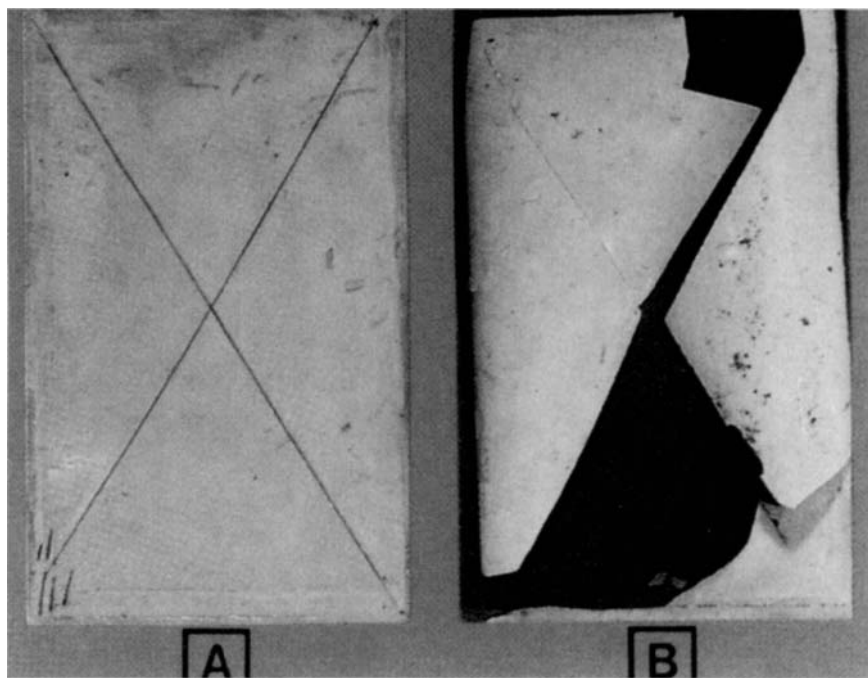
(b)

**Figure 10.2** The effect of LP-3 level (in parts LP-3 per 100 parts epoxy resin) on the pot-life of a diglycidyl ether of bisphenol A (DGEBA) epoxy resin for a 100 g mix at 22°C: (a) acceleration of cure (DGEBA epoxy resin with Ancamine 1608); (b) retardation of cure (DGEBA epoxy resin with Ancamine MCA). Redrawn with permission from Morton International Ltd, Coventry, UK

**10.2.1.4 Flexibility.** Outstanding flexibility and elasticity are shown by LP-epoxy systems, which is maintained even after extended spray exposure (Rees *et al.*, 1994).

**10.2.1.5 Thermal shock resistance.** Cured coating or adhesive can withstand, without fracturing, the expansion and contraction movements encountered during thermal cycling. A correctly formulated system can withstand the effects of thermal cycling over a wide temperature range, from  $-55^{\circ}\text{C}$  to  $85^{\circ}\text{C}$ .

**10.2.1.6 Weathering resistance.** A polysulphide molecule is very susceptible to ultraviolet (UV) or ozone attack because of the absence of unsaturation or carbonyl groups. The combination of such molecules with an epoxy resin will not prevent the yellowing associated with epoxy systems that have been subjected to continuous bright sunlight – although in some cases it may reduce this yellowing. However, the level of embrittlement that occurs when epoxy-based resins are subjected to high temperatures is significantly reduced (Figure 10.3).



**Figure 10.3** The weathering resistance of epoxy-polysulphide coatings after one month of outdoor exposure: [A] LP-epoxy modified coating; [B] unmodified epoxy coating. Substrate = oily, rusty and wet mild steel. Reproduced with permission from Morton International Ltd, Coventry, UK

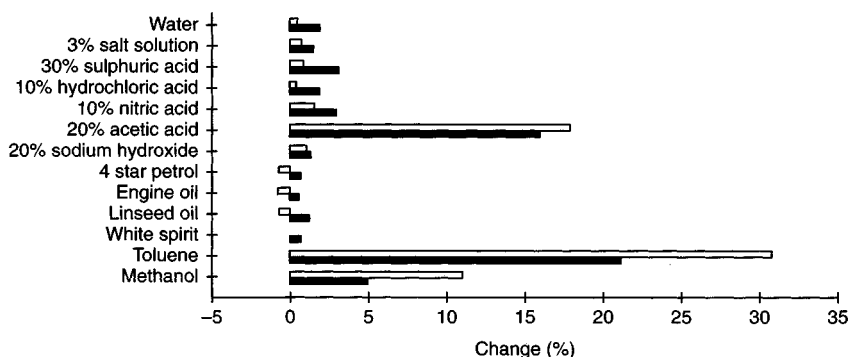
**10.2.1.7 Chemical resistance.** Unmodified epoxy resins have excellent resistance to dilute acids, alkalis and certain solvents. The incorporation of an LP component into the epoxy resin extends this resistance to a wide variety of oils, aromatic and aliphatic hydrocarbons, esters and ketones. Coatings and adhesives based on polysulphide-epoxy resins exhibit reduced swell and maintenance of flexibility and adhesion when immersed in these fluids. In view of this, LP-modified epoxies are used on oilrigs, fuel-storage installations and chemical plants (Figure 10.4).

**10.2.1.8 Impact resistance.** Modification with polysulphide changes the epoxy resin from a brittle to a ductile material (Figure 10.5).

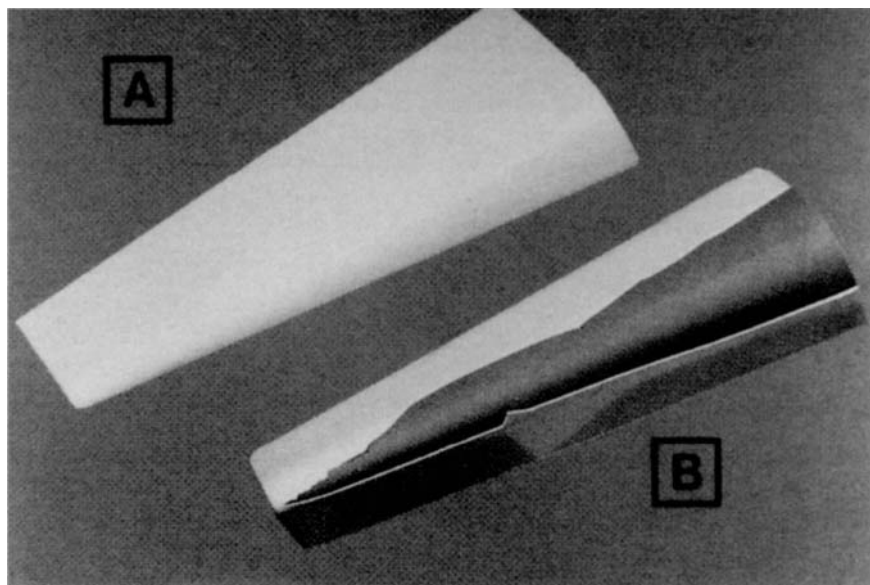
### 10.2.2 Compounding ingredients for epoxy-polysulphide systems

Apart from polymer and curatives, the other ingredients of epoxy-polysulphide systems are fillers, pigments, reinforcing agents and solvents.

Fillers extend the pot-life and reduce the cure exotherm. Calcium carbonates are, of course, the most commonly used fillers. Bentonite clays, fumed silica or talcs control the rheology of the system (Morton International, 1988). Dyes or inorganic pigments are suitable for colouring the epoxy-polysulphide systems. Fibrous or laminar fillers increase the rigidity and impact strength. Solvented or solventless systems can be formulated depending on application requirements. Owing to the very low viscosity of the polymer there is a need for only minimal solvent addition. Suitable solvents are ketones, esters, alcohols, chlorinated hydrocarbons and aromatic hydrocarbons.



**Figure 10.4** The chemical resistance of a diglycidyl ether of bisphenol A (DGEBA) epoxy resin modified with LP-3 (50 parts LP-3 per 100 parts resin). A 5 cm × 3 cm × 2 mm coupon was immersed in the liquid for 28 days at 23°C. Open boxes = percentage volume swell; shaded boxes = percentage weight change. Reproduced with permission from Morton International Ltd, Coventry, UK



**Figure 10.5** The effect of polysulphide modifications to epoxy coatings: [A] epoxy coating modified with polysulphide co-polymer; [B] unmodified epoxy coating. Reproduced with permission from Morton International Ltd, Coventry, UK

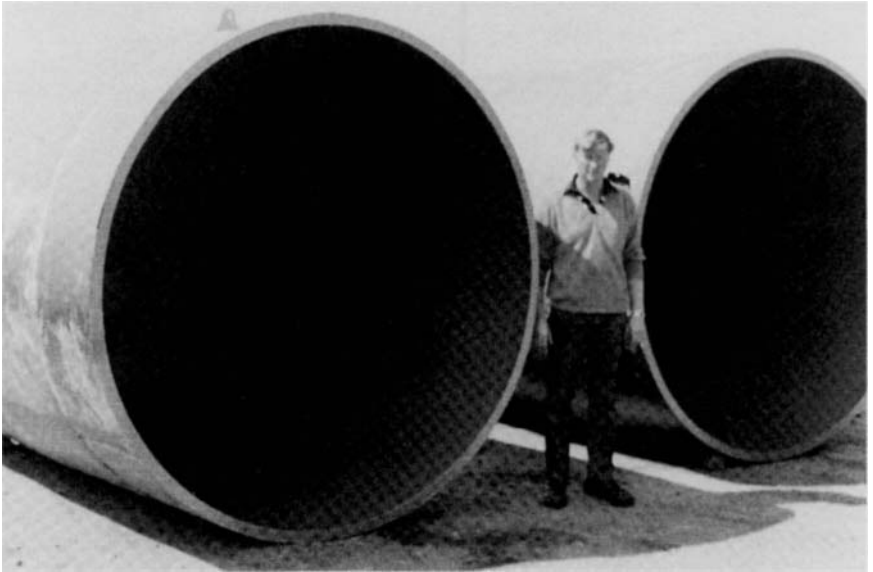
### *10.2.3 Specific applications in construction*

**10.2.3.1 Coatings.** Coatings based on epoxy-polysulphide combinations can be formulated to fulfil several end-uses such as marine coatings, oil-resistant and fuel-resistant coatings, impact-resistant and chemical-resistant floor coatings and intumescent and fire-protective coatings. These coatings are suitable for application as pipe linings, chute linings and fuel-resistant tank linings (Figure 10.6).

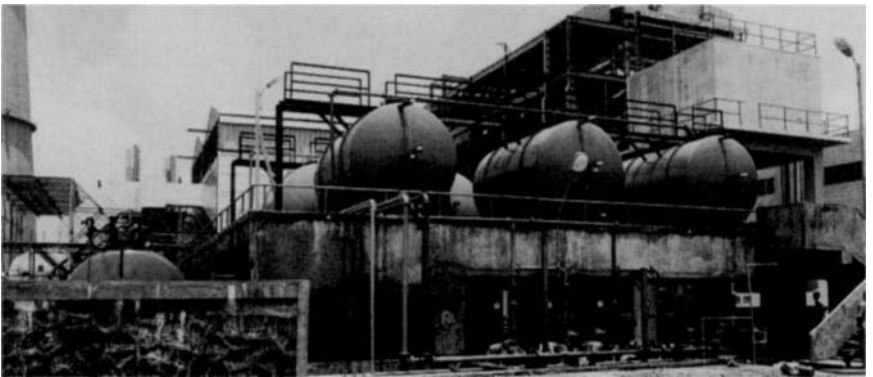
In 1993 epoxy-polysulphide based coatings were used to coat two 250 MW thermal power projects at Dhanu, about 100 km north of Bombay. The site is on the coast, less than 1 km from the sea and as such the nature of the local atmosphere is highly corrosive, with continuous sea breezes, and the soil is saturated with marine salt. The coating has shown satisfactory performance (Figure 10.7) (Morton International, undated c). This project was constructed under the control of Bombay Suburban Electricity Supply Co. Ltd (BSES).

Another example of epoxy-polysulphide coating application is for the Indian Molasses Co. Ltd tank farm facilities in Mangalore where the nature of the atmosphere is highly corrosive. Several tanks have been coated (Figure 10.8) (Morton International, undated d).

Epoxy-polysulphide coatings exhibit excellent adhesion to steel, aluminium and concrete without the use of primers (Morton International,



**Figure 10.6** The use of polysulphide-epoxy coatings as pipe linings. Reproduced with permission from Morton International Ltd, Coventry, UK

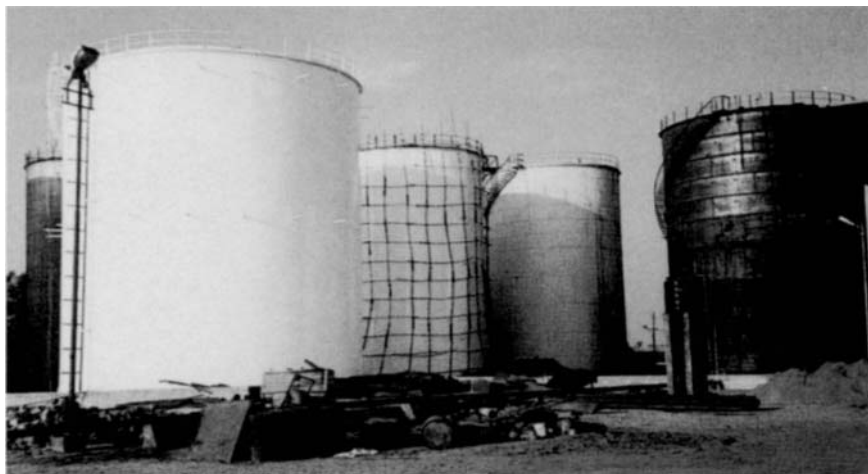


**Figure 10.7** Epoxy-polysulphide coating used in a thermal power project at Dhanu, India. Reproduced with permission from Morton International Ltd, Coventry, UK

1988). Good impact resistance, abrasion resistance, mar resistance and chemical resistance are other key benefits.

**10.2.3.2 Adhesives.** Epoxy-polysulphide adhesives are elastomeric in nature. Therefore, they can withstand movement and vibration. They reduce stress between dissimilar bonded materials. They are used as





**Figure 10.8** Epoxy-polysulphide coating at Indian Molasses Co. Ltd, Mongalore. The tank on the front left-hand side has two coats. The next tank on the right has its second coat almost completed. The third tank has received one coat. The tank on the far right-hand side is being prepared to receive its first coat. Reproduced with permission from Morton International Ltd, Coventry, UK

structural and semistructural adhesives for steel and aluminium, crack repair adhesives for concrete and as patch-repair compounds and grouting compounds (Morton International, 1988; Rees *et al.*, 1994).

### 10.3 Epoxy-polyurethanes

Epoxy resins produced by the reaction of bisphenol A and epichlorohydrin are versatile polymers with several useful properties (subsection 2.2.2.1). However, one significant weakness is their brittle nature. Incorporation of plasticisers is not very useful. Dibutyl phthalate is an exception, showing good compatibility but offering only limited ability to flexibilise the resin. Moreover, plasticisers affect the mechanical properties and chemical resistance of the cured system. With polyurethanes it is possible to complement the flexibility of the epoxy system. Numerous attempts have been made to combine the two types to achieve beneficial modifications (Lee and Nivelles, 1967). These modifications proved successful under high-temperature cure but inferior results were obtained for ambient cures.

Successful attempts have been made in the last few years and now it has become practical to have ambient-curing products based on epoxy-polyurethane hybrids. In this section the developments based on the work

of two different companies will be highlighted. The first development is based on the work of W. Welner, H. Gruber and G. Ruttmann of Bayer AG (Welner *et al.*). This work involved the use of polyaddition compounds based on toluene di-isocyanate, propylene glycol (PPG) ether and alkyl phenol. Urethanes obtained from such a route have the tendency to react with polyamines commonly used in epoxy chemistry. Two different poly-reactions have been considered:

- epoxy resin with polyamine – polyaddition;
- urethane polymer with polyamine – polycondensation.

It is possible to accelerate the rate of the polycondensation reaction by incorporation of special catalysts, resulting in urethane–urea-modified epoxy resin. The low-volatility alkyl phenol liberated in this reaction remains in the film as an external plasticiser. Owing to the different rates of the above two reactions, they have been synchronised to produce suitable polymer segments (Figure 10.9).

Products based on the above modifications have shown the following improvements:

- additional extension in the temperature range for torsion modulus;
- high elongation at break;
- appreciable increase in intercoat adhesion, even on ageing;
- good mechanical properties and chemical resistance.

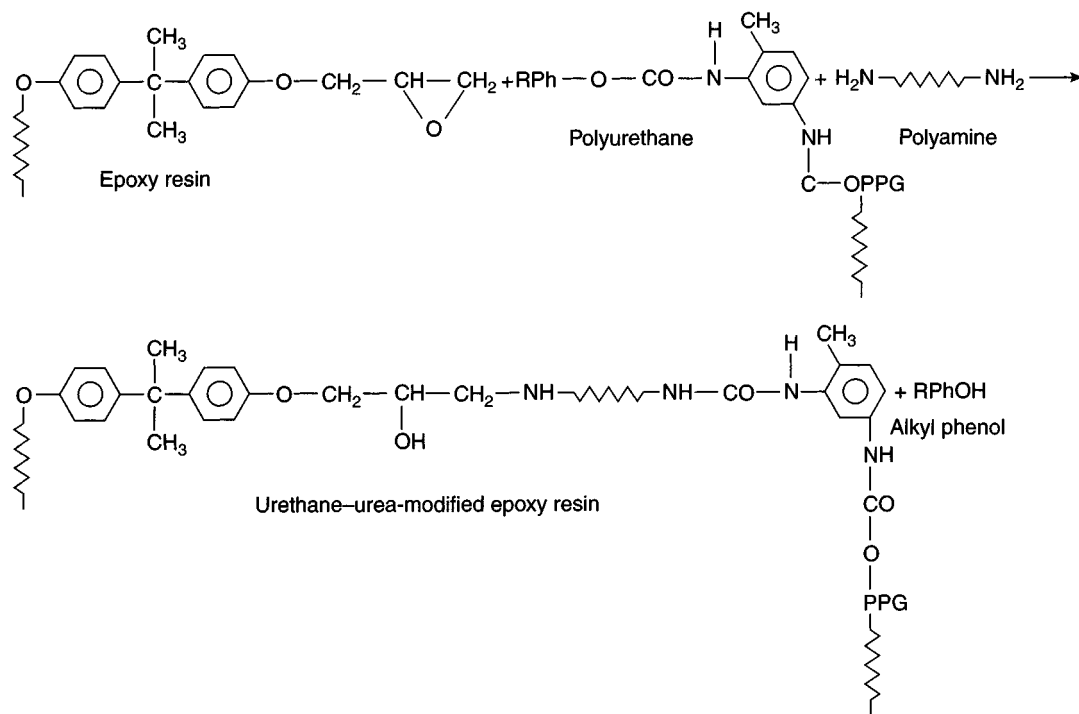
The system can be formulated with fillers, pigments and auxiliaries. They cure with aminic hardeners at room temperature according to the two-pack process. Specific construction applications with the above development are as follows:

- highly flexible, weather-resistant roof coatings;
- floor coatings.

Both of the above systems are solvent-free.

Another development has been reported by P.A. Lucas, W.E. Starner and S.G. Musselman of Air Products and Chemicals Inc. (Lucas *et al.*, 1994). An acrylate functional urethane flexibiliser has been used to modify epoxy resin, which optimises reactivity and is more compatible with epoxy. Urethane–acrylate flexibiliser offers very tough hybrid epoxy systems meeting the more demanding requirements of civil engineering applications.

Epoxyes modified with acrylate functional urethane are suitable for application in coatings and adhesives.



**Figure 10.9** The reaction pattern for epoxy-polyurethane modifications. Source: Wellner, W., Gruber, H. and Ruttman, G., *New solvent free epoxy/polyurethane combinations*, publication E 908-8122/850640; published by Bayer AG, Plastics and Coatings Division, D-5090, Leverkusen

## 10.4 Epoxy-acrylates

A combination of epoxy and acrylic offers an interesting means of modifying both types of resin. Methacrylic acid as well as high molecular weight polymerised acrylic acid or acrylic acid co-polymers may be cross-linked with epoxies. Systems with low volatile organic content can be formulated with epoxy-acrylic hybrids. Water-borne epoxy-acrylics have also been developed. These are formed by hydrogen abstraction from the epoxy backbone. The introduction of a carboxylic acid group, through the use of a carboxy functional acrylic monomer in a graft co-polymerisation at these backbone sites is the mechanism by which the epoxy is rendered water-dispersible (Figure 10.10) (Oldring, 1996).

M.A. Bailey, T. Cauffman and R. Costin (Bailey *et al.*, 1996) have developed a new line of low-volatility acrylic monomers and oligomers containing reactive carbon-carbon double bonds. These products readily undergo Michael addition polymerisation reactions with conventional amine curing agents. When an acrylic monomer or oligomer is used as a modifier for an epoxy resin in a high-solids coating formulation, the amine curing agent reacts with the epoxy resin via direct addition and the acrylic monomer/oligomer via Michael addition to give a highly cross-linked thermoset network. In this system, the acrylic components provide viscosity reduction and reinforce the epoxy cross-link network, thereby contributing to the final properties of the coating. Hence the acrylic monomer not only functions as a diluent for the epoxy resin but also becomes part of the coating. In this way, very low volatile organic content, high-performance epoxy-based systems can be formulated.

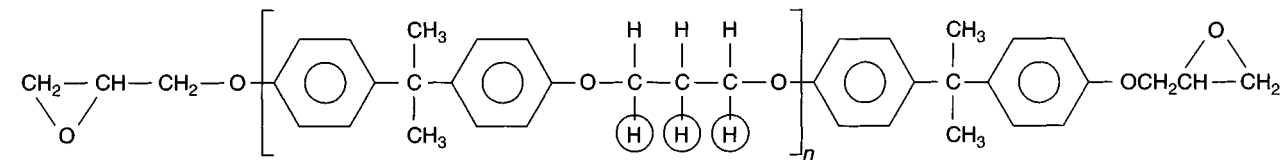
## 10.5 Polyurethane-acrylics

Polyurethane dispersions (PUDs) can be hybridised with acrylics. The compatibility of both resins displays several important benefits (Howarth and Manok, 1996):

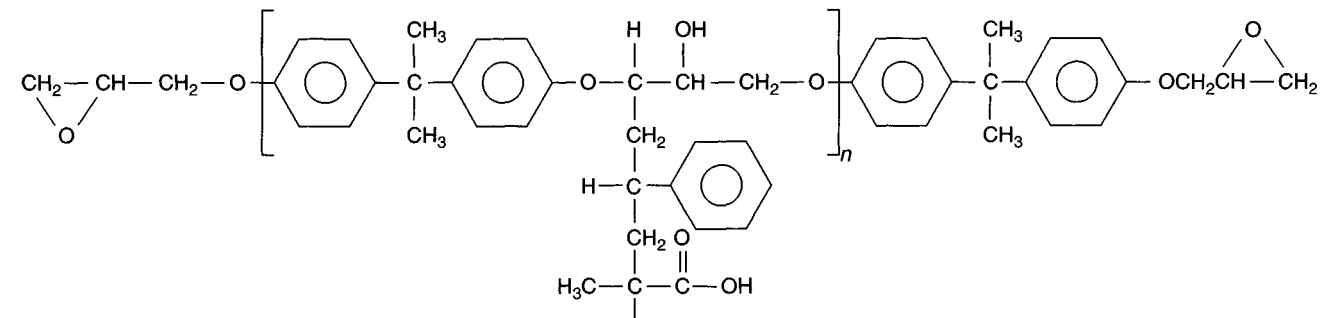
- improved low-temperature flexibility;
- improved chemical and solvent resistance;
- improved impact resistance;
- improved abrasion resistance;
- improved early block resistance.

Hybrid based on PUD-acrylics are basically of two types:

- simple blend of PUD with acrylic emulsion polymer;
- a true copolymer formed by chemically linking the PUD and acrylic functionality in the backbone of polymer chain.



(a)



(b)

**Figure 10.10** (a) Grafting sites (ringed hydrogens) on the epoxy resin backbone; (b) epoxy-acrylic graft structure

Hybridisation techniques enable the solids content of PUDs to be increased. However, this is achieved at the expense of volatile organic content, although this is satisfactorily low (Howarth and Manok, 1996).

In spite of vast research work on PUD-acrylic hybrids, a limited range of hybrids is currently available. Among the various systems, two types are of interest to the construction industry. The first type is suitable for concrete protection, in the form of coatings. The second type finds suitability for wood finishes for parquet floor lacquers.

## 10.6 Silylated urethanes

This development was reported in 1995 by T.-M. Feng and B.A. Waldman (1995) of Osi Specialities Inc (now part of Witco). Silane-endcapped urethane polymers generally consist of urethane backbones, prepared at a low NCO:OH ratio, with reactive organofunctional silane groups at the end.

### 10.6.1 Chemistry

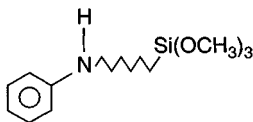
Silane-endcapped urethane polymers are prepared in a two-step process:

- synthesis of the NCO-terminated urethane prepolymer;
- preparation of silylated urethane polymer.

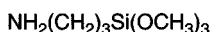
Feng and Waldman used 4,4'-diphenylmethane diisocyanate. The polyol is either 2000 or 4000 molecular weight polypropylene glycol (PPG) and the catalyst is dibutyltin dilaurate (DBTDL). The NCO-terminated urethane prepolymers are made in the usual way by reacting an excess of methane diisocyanate with PPG in the presence of DBTDL at an NCO : OH ratio of 1.4 : 2.0. The reactions are run at 70°C for about 3 h to reach a constant percentage of NCO.

The organofunctional silane is added to the prepolymer for endcapping under the same reaction conditions. Silanes used to endcap the prepolymer include:

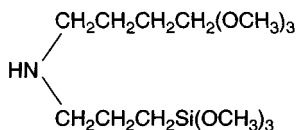
- phenylaminopropyltrimethoxy silane (trade name Silquest Y-9669)



- aminopropyltrimethoxy silane (Silquest Y-1110)



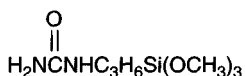
- bis[(3-trimethoxysilyl)propyl] amine (Silquest A-1170)



- mercaptopropyltrimethoxy silane (Silquest A-189)



- ureidopropyltrimethoxy silane (Silquest Y-11542)



### 10.6.2 Applications

Silylated urethane polymers allow formulators to produce fast-cure construction joint sealants with superior performance properties. The sealant is composed of silylated urethane polymer, plasticiser (e.g. diisodecyl phthalate), fillers (calcium carbonates), fumed silica, adhesion promoter, dehydrating agent, and catalyst (dibutyltin dilaurate).

A model sealant is reported to exhibit high elongation and good tensile and tear strength. The sealant finds suitability as a low-to-medium-modulus construction joint sealant.

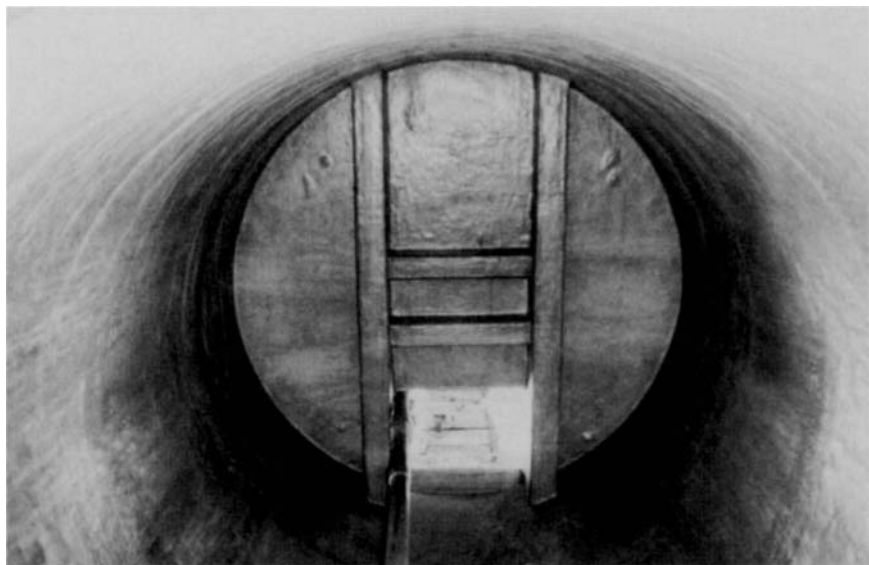
Silylated urethane polymer technology is an alternative to, and an extension of, existing conventional urethane technology. The sealants are free of residual NCO. This technology is moving from a theoretical concept to practical commercial applications.

## 10.7 Vinyl-epoxies

The combination of vinyl resins with epoxies is useful in formulations of solution coatings. Desirable characteristics are offered by low cost and high oxidation resistance of the vinyl resin.

Polyvinyl acetals improve the impact resistance of DGEBA resins when employed with Lewis-acid-type curing agents. With phenolformaldehyde curing agents they improve the peel and impact resistance of DGEBA adhesive formulations (Lee and Nivelles, 1967).

The stabilising action on vinyls arises in part from the ability of the epoxy groups to react with hydrogenchloride liberated during exposure of the vinyl formulation to heat and/or light (Lee and Nivelles, 1967).



**Figure 10.11** Cured-in-place pipe rehabilitation. Reproduced with permission from Dow Chemical Company, Midland, MI, USA

Epoxy modification provides the ability to cross-link with carboxyl-modified vinyl resins to give an all-vinyl reactive system that yields thermoset-like characteristics, most notably improved toughness, enhanced physical properties and superior chemical resistance (Union Carbide Corp., 1996).

Coatings based on vinyl-epoxies are used as corrosion barrier coatings for storage tanks containing corrosive chemicals. Vinyl-epoxies are a very efficient and long-lasting means of protection for the repair of cured-in-place pipes. This is comparable to replacing a pipe.

Vinyl-epoxies have been used in the Houston city rehabilitation programme for the rehabilitation of cured-in-place pipes. The deteriorated pipes (made of polyester felt) were impregnated with vinyl-epoxy resin and perforated with tiny holes, allowing a calculated amount of excess resin to migrate to the wall and adhere to the existing pipe during installation. The tube was then pulled into the host pipe and inflated through the use of hydrostatic pressure. Hot water was circulated through the pipe to cure the resin-impregnated tube, forming a rigid 'pipe within a pipe' (Figure 10.11) (personal communication, 27 November 1996, from Dow Chemical Co., Midland, MI, USA).



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## Appendix A Glossary

**Abrasion** The wearing away of materials by friction.

**Abrasion resistance** The ability of a surface to resist being worn away by rubbing and friction.

**Accelerator** An ingredient used in small amounts to increase the rate at which a curing agent acts. It is sometimes used as a synonym for 'curing agent'.

**Additive** Any substance incorporated into a base material, usually in low concentrations, to perform a specific function (e.g. antioxidants, stabilisers, colorants, inhalators, thickeners, driers, dispersing agents, viscosity index improvers, biocides).

**Adduct** An unbounded association of two molecules in which a molecule of one component is either wholly or partly locked within the crystal lattice of the other.

**Adhesion** The tendency of a material to bond to another substance or material when under a separating stress.

**Adhesion promoter** An ingredient which improves the adhesion of a material to particular substrate(s).

**Adhesive** A substance having the capability of maintaining surface attachment by means of interfacial forces between two or more surfaces.

**Adhesive failure** The failure of an adhesive material by pulling away from the surface with which it is in contact

**Ageing** The progressive change in physical or chemical properties of a material with time.

**Agglomeration** A combination or aggregation of colloidal particles suspended in a liquid into clusters of approximately spherical shape.

**Aggragate** A compounding ingredient generally used to reduce the cost of materials.

**Air entrapment** The development of minute bubbles because of the improper release of air from the system.

**Algae** Chlorophyll-bearing organisms occurring in both saltwater and freshwater; they have no flowers or seeds but reproduce by means of unicellular spores. They range in size from single cells to a giant kelp.

**Aliphatic compounds** A group of organic compounds characterised by a straight-chain or branched-chain arrangement of the constituent carbon atoms (e.g. alkanes, alkenes).

**Alkaline** The condition of having or containing hydroxyl (OH) ions.

**Allophanate** An unsaturated nitrogenous product made by reaction of an alcohol with two moles of isocyanic acid (a gas).

**Ambient temperature** The temperature of the air surrounding the object under construction.

**Amines** A class of organic compounds of nitrogen that may be considered as derived forms of ammonia ( $\text{NH}_3$ ), with one or more of the hydrogen atoms replaced with an alkyl group.

**Antioxidant** A compounding ingredient used to retard deterioration caused by oxidation.

**Aromatic** A major group of unsaturated acrylic hydrocarbons containing one or more rings; these are typified by benzene, which has a six-carbon ring containing three double bonds.

**Back-up or backing** A compressible material used in the bottom of sealant joints to reduce the depth of sealant and to improve its shape factor.

**Bacteria** Microorganisms often composed of single cells, in the form of straight or curved rods (bacilli), spheres (cocci), or spiral structures.

**Barrier cream** Preparatory protective creams that are applied to skin (particularly hands) before working in a chemical environment.

**Biocide** Any substance that kills or inhibits the growth of microorganisms such as bacteria, moulds, slimes and fungi. Many of them are also toxic to humans.

**Biodegradation** Degradation of a material owing to the effect of bacteria, fungi, lichens and so on.

**Biuret** The common name for carbonyl urea. Its structure is  $\text{NH}_2\text{CONHCONH}_2 \cdot \text{H}_2\text{O}$ .

**Blistering** The formation of cavities or sacs which deform the surface of the material.

**Bond breaker** A material used to prevent sealant adhesion at a designated interface.

**Butt joint** A joint in which the structural units are joined to place sealant into tension or compression between the joint faces.

**Carbonation** The conversion of calcium hydroxide in hardened cementitious material to calcium carbonate by reaction with atmospheric carbon dioxide.

**Carbon black** A finely divided form of carbon made by the incomplete combustion or thermal decomposition of natural gas or petroleum oil.

**Castor oil** A non-drying oil derived from the seeds of the castor bean, *Ricinus communis*. It is a pale yellowish or almost colourless transparent, mixed liquid. It is used in paint and has a mild odour and a nauseating taste.

**Catalyst** A substance added in small quantities to promote a reaction while remaining unchanged itself. It is sometimes referred to as a 'curing agent'.

**Chalking** The formation of a powdery surface as a result of weathering.

**Chloride content** The total amount of chloride ions present in concrete or mortar.

**CIRIA** The abbreviation from the Construction Industry Research and Information Association.

**Coal tar** A black viscous liquid or semisolid obtained by the destructive distillation of bituminous coal. It has a naphthenate-like odour, is toxic by inhalation and is a known carcinogen.

**Coating** A material that provides a protective or decorative function to the substrate.

**Compression seal** A seal which is attained by compressive force on the sealing material.

**Compression set** The amount of permanent set that remains in a specimen after removal of a compression load.

**Concrete** A mixture comprising sand, portland cement and a conglomerate of gravel, broken stones, pebbles and water in a particular ratio, setting to form a hard mass.

**Construction joint** A joint at a predetermined location where two successive placements of concrete meet.

**Contraction joint** A joint between building components where the only movement to be expected is from the shrinkage of either or both components.

**Corrosion** The degradation of concrete or steel reinforcement by electrochemical or chemical attack.

**Cracking** The complete or incomplete separation of concrete into two or more parts as a result of breaking or fracturing.

**Cross-linking** The attachment of two chains of polymer molecules by bridges composed of either an element, a group or a compound which join certain carbon atoms of the chains by primary chemical bonds. Cross-linking increases the strength, heat and electrical resistance of the polymer and makes the polymer particularly resistant to solvents and other chemicals.

**Crystallisation** The purification of materials by evaporation and solidification.

**Curing** The irreversible hardening of a material by chemical reaction or solvent evaporation.

**Curing time** The period between application and the time when the material attains its intended physical properties.

**Curtain wall** A type of construction in which the walls of the building are non-structural, usually made of glass or metal and glass or from other composite product panels.

**Cycloaliphatic compounds** A class of unsaturated cyclic organic compounds.

**Dehydrogenation** The process in which hydrogen is removed from compounds by chemical means.

**De-icing salts** Compounds that prevent the formation of ice (e.g. calcium chloride, sodium chloride).

**Dielectric constant** A value that serves as an index of the ability of a substance to resist the transmission of an electrostatic force from one charged body to another; the lower the value, the greater the resistance.

**Diels–Alder reaction** A reaction involving the addition of an ethylenic double bond to a conjugated diene.

**Diluent** A liquid which lowers the viscosity and increases the bulk but is not necessarily a solvent for the solid ingredients.

**Distillation** A separation process in which a liquid is converted to vapour and the vapour then condensed to a liquid. The purpose of distillation is purification or separation of the components of a mixture.

**Dry film thickness (DFT)** The thickness of the applied coating on a substrate in completely dry conditions.

**Efflorescence** The loss of combined water molecules by a hydrate when exposed to air, resulting in partial decomposition indicated by the presence of a powdery coating on the material.

**Elongation** The extension produced by tensile stress.

**Emulsion** A stable mixture of two or more immiscible liquids held in suspension by small percentages of substances called emulsifiers.

**Encrustation** The formation of a crust on the surface of a material.

**Ester** An organic compound derived from acids by the exchange of the replaceable hydrogen of the acid for an organic radical. The general structure is as follows:



**Ether** An organic compound in which an oxygen atom is interposed between the two carbon atoms (or organic groups) in the molecular structure, giving the generic formula ROR'.

**Eutectic** When a mechanical mixture of two or more substances shows a sharp melting point, the mixture is said to be eutectic. The temperature at which it occurs is called the eutectic temperature.

**Evaporation** The change of a substance from the solid or liquid phase to the gaseous or vapour phase.

**Exothermic** A process or chemical reaction which is accompanied by the evolution of heat.

**Expansion joint** A structural separation between building elements that allows independent movement without damage to the assembly.

**Filler** An inert powder used to provide a certain degree of stiffness and hardness and to decrease cost.

**Film forming temperature** The minimum temperature required by a coating to dry.

**Filtration** The operation of separating suspended solids from a liquid (or gas) by forcing the mixture through a porous barrier.

**Floor topping** A polymeric material applied on concrete floors for a specific reason. Screed floorings and self-levelling floors are included in this category.

**Free radical** A molecular fragment having one or more unpaired electrons, usually short-lived and highly reactive. In chemical formulae a free radical is conventionally indicated by a dot, as in  $(C_2H_5)^\cdot$ .

**Fungicide** A substance which kills or inhibits the growth of fungi.

**Fungus** Any of a plant-like group of organisms that does not produce chlorophyll; they derive their food either by decomposing organic matter from dead plants and animals or by parasitic attachment to living organisms, thus often causing infection and disease.

**Gardener colour** A measure of translucency as seen in the case of liquid epoxy resins. The Gardener scale ranges from 1 to 10. Transparent materials have a lower value on the Gardener scale.

**Gel time** The period of time from the initial mixing of the reactants in a composition to the time when gellation occurs.

**Glass transition temperature ( $T_g$ )** The temperature at which an amorphous material (e.g. high polymer) changes from a brittle, vitreous state to a plastic state.

**Glazing** The installation of glass or other material in prepared openings.

**Gloss** The shine, sheen or lustre of the surface of a coating.

**Glycol** A general term for dihydric alcohols (e.g. ethylene glycol).

**Grout** A stable material (cementitious or polymeric) which after having been applied in a plastic, flowable or fluid state will set to fill a void to the required performance.

**Gun-grade sealant** Thixotropic sealants are commonly referred to as 'gun-grade sealants' as they are applied with the aid of an application gun.

**Hairline cracks** Small cracks of a random pattern in an exposed concrete surface.

**Hardener** A chemical that is added to the polymer base to form a solid material; also known as a 'curing agent'.

**Hardness** The resistance to indentation as measured under specific conditions.

**Heat distortion temperature (HDT)** The temperature at which the properties of a polymeric material are distorted.

**Heterocyclic** This designates a closed-ring structure, usually 5-membered or 6-membered, in which one or more of the atoms in the ring is an element other than carbon (e.g. sulphur, nitrogen, etc.).

**Homopolymerisation** The process of formation of synthetic high polymers from a single monomer.

**Honeycomb** A defect in concrete structures arising from poor compaction, resulting in weak concrete.

**Hydantoin** Glycol urea is commonly known as hydantoin.

**Hydrolysis** A term used to signify reactions due to the presence of the hydrogen or hydroxyl ions of water.

**Hydrophilic** Having a strong tendency to bind to or absorb water.

**Hydrophobic** Having no attraction for water.

**Impact** The single instantaneous stroke or contact of a moving body with another, either moving or at rest.

**Impact strength** The ability of a material to accept a sudden shock without fracture or other substantial damage, as measured by standard impact testing equipment.

**Impregnation** A process of filling the interstices of a porous body with polymer compound.

**Inhibitor** A general term for any compound which will inhibit (i.e. slow down or stop) a reaction, generally by preventing propagation of the chain reaction or by passivation of surfaces, etc. The term is often used to describe any additive which will prevent a particular tendency during working operations (e.g. antioxidants, anticorrosion agents).

**Insulator** Any substance that has an extremely low dielectric constant, low thermal conductivity or both.

**Intumescent** A material that foams and swells when exposed to high surface temperature or flames is said to be intumescent.

**Isocyanate** A substance containing an isocyanate ( $-\text{N}=\text{C}=\text{O}$ ) group. A polyisocyanate contains more than one isocyanate group.

**Isomers** Molecules of the same atomic composition and molecular weight but of different geometric configuration.

**Joint** The space or opening in a building between two or more adjoining surfaces.

**Joint movement** The difference in width of a joint opening between the fully open position and the fully closed position.

**Joint sealant** A compressible material used to exclude water and solid foreign materials from joints.

**Ketimines** A type of curing agent for epoxy resins which makes it possible to use very high-solids-content coatings in spray equipment. They react with epoxies very slowly and thus delay curing time, which prevents the resin from setting during the spraying operation.

**Lactone** Anhydrides formed by intermolecular elimination of water between the hydroxyl and carboxyl groups of hydroxy acids.

**Laitance** A weak layer of non-durable materials containing cement and fines from aggregates on a concrete surface that is usually caused by an overwet mixture, overworking of the mixture, improper or excessive finishing or combinations thereof.

**Latex** An emulsion of natural or synthetic rubber in the water phase.

**LD<sub>50</sub>** The quantity of a substance administered either orally or by skin contact which kills 50% of animals exposed to it in laboratory tests within

a specified time. A substance having an  $LD_{50}$  of less than 50 mg/kg body weight is rated as highly toxic by toxicologists.

**Mercaptan (thiol)** Any group of organic compounds resembling alcohols but having the oxygen of the hydroxyl group replaced by sulphur. They are characterised by strong and repulsive odour.

**Modulus** As related to sealants used in building construction, it is the stress (force/unit area) at a corresponding strain (elongation) expressed as a percentage of the original dimension.

**Moisture vapour transmission (MVT)** A measurement of the transmission of moisture vapour through a film, usually expressed in terms of grammes of water per square metre per 24 hours.

**Molar** A concentration in which one mole of a substance is dissolved in enough solvent to make one litre of solution. It is indicated by the symbol M. Molar quantities are proportional to the molecular weights of the substances.

**Molecular weight** The sum of atomic weights of the atoms in a molecule.

**Mortar** A mixture of cement, lime, sand and water.

**Movement accommodation factor (MAF)** A method for assessing the ability of a sealant to accommodate movement. It is used in the design of a joint to ensure that there is sufficient sealant present to accommodate the likely movement in the joint.

**Movement joint** See expansion joint.

**Osmosis** The passage of liquid (e.g. water) into a solution (e.g. of sugar and water) through a membrane that is permeable to the liquid but not to the solute.

**Oleophobic** Having no attraction for oil.

**Oxidation** The formation of oxide; also the deterioration of a rubbery material as a result of the action of oxygen or ozone.

**Ozone** A reactive form of oxygen molecule ( $O_3$ ); a powerful oxidising agent occurring in the atmosphere.

**Paraffin wax** A white, translucent, tasteless, odourless solid, consisting of a mixture of solid hydrocarbons of high molecular weight (e.g.  $C_{36}H_{74}$ ).

**Peroxide** A compound containing a bivalent O—O group (i.e. the oxygen atoms are univalent). Such compounds readily release atomic (nascent) oxygen and thus they are strong oxidising agents and fire hazards when in contact with combustible materials, particularly under high-temperature conditions. Organic peroxides are used as sources of free radicals for free-radical polymerisation.

**pH** Hydrogen ion concentration; the negative logarithm (to the base of 10) of the hydrogen ion concentration of a solution.

**Pigment** Any substance, usually in the form of dry powder, that imparts colour to another substance or mixture.

**Pitch** A carbonaceous tacky residue resulting from the distillation of coal tar.



**Plasticiser** An organic compound added to a high polymer both to facilitate processing and to increase the flexibility and toughness of the final product by internal modification of the polymer molecule.

**Polyether** A polymer with  $n[\text{C}—\text{O}—\text{C}]$  units in the backbone, derived from aldehydes or epoxides or similar materials.

**Polyisobutylene (polybutylene, polybutene, polyisobutene)** Any of several thermoplastic isotactic polymers of isobutene of varying molecular weight. They are used as major components in sealing and caulking compounds.

**Polymer concrete or mortar** A concrete or mortar in which a resin serves as a binder.

**Polymerisation** A chemical reaction, usually carried out with a catalyst, heat or light and often under high pressure, in which a large number of relatively simple molecules combine to form a chain-like macromolecule.

**Polyol** A substance containing several hydroxyl groups. Diols, triols and tetrols contain two, three and four hydroxyl groups, respectively.

**Pot-life** The time interval after mixing the components of a multicomponent product during which application is possible.

**Prepolymer** A polyurethane reaction intermediate made by reacting isocyanate with a polyester or polyether, in which one component is in considerable excess of the other.

**Primer** A compatible coating designed to enhance adhesion.

**Redispersible powder** Polymers typically produced by spray-drying isolation of the specially designed latex such as those of acrylics, vinyl acetate, etc. Depending on the nature of the resin type, a suitable amount of inorganic filler is added to the powders to prevent caking.

**Render** Cementitious repair mortar; cements modified with polymers are included in this category.

**Resilience** A measure of the energy stored and recovered during a loading cycle. It is expressed as a percentage.

**Resin** Certain liquid prepolymer products, such as epoxies and unsaturated polyesters, which are subsequently cross-linked to form hardened polymer.

**Screed** A system based on polymeric binder and sand aggregates. Such systems are applied by trowel as industrial floorings.

**Sealant** A material that has the necessary adhesive and cohesive properties to form a seal.

**Self-levelling sealant** A sealant that is fluid enough to be poured into horizontal joints. It forms a smooth level surface without tooling; also referred to as 'pouring-grade sealant'.

**Sewage** Wastewater from domestic or industrial sources.

**Shear test** A method of deforming a sealed or bonded joint by forcing the substrates to slide over each other.

**Shelf-life** The maximum length of time a product may be stored prior to use without adversely affecting its properties.

**Shore A hardness** The measure of firmness of a rubbery compound or sealant by means of a durometer hardness gauge.

**Shrinkage** The decrease in volume caused by evaporation of solvent or loss of oil or vehicle into a porous surface.

**Silane** A solution of a low molecular weight composition of silicon and hydrogen used as a penetrating sealer for concrete surfaces.

**Siloxane** A silicon and oxygen based compound, also containing carbon and hydrogen, used as a penetrating sealer for concrete surfaces.

**Solvent** A liquid in which another substance can be dissolved.

**Spalling** A surface failure of concrete usually occurring at the joint or at the exposed face. It may be caused by overworking the concrete, by de-icing salts and so on.

**Staining** The change in colour or appearance of the surface of the substrate adjacent to an applied sealant. This change is usually penetrating, and the colouring is transparent and without surface film.

**Stoichiometric** The characteristic proportions of chemical reaction, obtained from chemical formulae, equations, atomic weights and molecular weights. Stoichiometry determines what and how much is used and produced in a chemical process.

**Stucco** A plaster used for coating exterior walls and other exterior surfaces of a building.

**Substrate** An adherend.

**Surfactant** Any compound that reduces surface tension when dissolved in water or water solutions or which reduces the interfacial tension between two liquids or between a liquid and a solid.

**Tear strength** The load required to tear apart a specified sealant, the load acting substantially parallel to the major axis of the test specimen.

**Tensile strength** The resistance of a material to a force that tends to pull it apart.

**Thermal oxidation** An oxidation reaction induced by heat.

**Thermal shock** The effects caused by heat on polymeric floorings and coatings.

**Thermodynamics** A rigorously mathematical analysis of energy relationships involving heat, work, temperature and equilibrium. It describes systems whose states are determined by thermal parameters, such as temperature, in addition to mechanical and electromagnetic parameters.

**Thermosetting** A material which hardens by chemical reaction and is not remeltable.

**Thixotropic** A non-sagging material which maintains its shape until agitated. A thixotropic sealant can be placed in a joint, vertically or horizontally, and will maintain its shape without sagging during the curing process.

**Tooling** The act of compacting and contouring a sealant in a joint.

**Toxic** Poisonous or dangerous to humans by swallowing, inhalation or by contact (resulting in eye or skin irritation).

**Vapour pressure** A component of atmospheric pressure which is caused by the presence of vapour.

**Veneer** A masonry facing which is attached to the back-up, but not so bonded as to act with it under load.

**Viscosity** A measure of the flow properties of a liquid or paste.

**VOC** An abbreviation for volatile organic compounds.

**Vulcanisation** A process in which rubber, through a change in its chemical structure, is converted to a condition in which the elastic properties are conferred or improved.

**Water-cement ratio** The ratio of the amount of water, exclusive to that absorbed by the aggregates, to the amount of cement in a concrete or mortar mix.

**Waterproofing** The treatment of a surface or structure to prevent the passage of a liquid such as water under hydrostatic, dynamic or static pressure.

**Water repellent** Any material which when impregnated into masonry structures prevents the ingress of water.

**Weathering** Changes in colour, texture, strength or chemical composition caused by the effects of the environment.

**Wet film thickness** The thickness of the liquid coating as it is applied.

## Appendix B Conversion tables

**Table B.1** Imperial–metric and metric–imperial conversion table

Unit	Equivalent
<b>Length:</b>	
inch (in)	2.54 centimetres (cm)
foot (ft)	30.48 centimetres (cm)
yard (yd)	0.91 metre (m)
mile (mi)	1.60 kilometres (km)
millimetres (mm)	0.04 inch (in)
centimetres (cm)	0.39 inch (in)
metre (m)	3.28 feet (ft)
kilometre (km)	0.62 mile (mi)
<b>Area:</b>	
square inch (in <sup>2</sup> )	6.45 square centimetres (cm <sup>2</sup> )
square foot (9ft <sup>2</sup> )	0.09 square metre (m <sup>2</sup> )
square yard (yd <sup>2</sup> )	0.83 square metre (m <sup>2</sup> )
square mile (mi <sup>2</sup> )	2.58 square kilometres (km <sup>2</sup> )
square centimetre (cm <sup>2</sup> )	0.16 square inch (in <sup>2</sup> )
square metre (m <sup>2</sup> )	1.19 square yards (yd <sup>2</sup> )
square kilometre (km <sup>2</sup> )	0.38 square mile (mi <sup>2</sup> )
<b>Mass:</b>	
ounce (oz)	28.34 grammes (g)
pound (lb)	0.45 kilogramme (kg)
short ton (2000 lb)	0.90 tonne (t)
gramme (g)	0.035 ounce (oz)
kilogramme (kg)	2.20 pounds (lb)
tonne (1000 kg) (t)	1.10 short tons
<b>Volume:</b>	
fluid ounce (fl oz)	29.57 millilitres (ml)
pint (pt)	0.47 litre (l)
quart (qt)	0.95 litre (l)
gallon (gal.)	3.78 litres (l)
millilitre (ml)	0.03 fluid ounce (fl oz)
litre (l)	2.11 pints (pt)
litre (l)	1.06 quarts (qt)
litre (l)	0.25 gallon (gal.)
<b>Temperature:</b>	
Fahrenheit (°F)	$\frac{5}{9}$ degrees Celsius (°C) + 32
Celsius (°C)	$\frac{5}{9}$ degrees Fahrenheit (°F) – 32
<b>Pressure, stress and modulus of elasticity:</b>	
pounds per square inch (psi)	145 Newtons per square millimetre (N/mm <sup>2</sup> , or MPa or MN/m <sup>2</sup> )
kilogrammes per square centimetre (kg/cm <sup>2</sup> )	10 N/mm <sup>2</sup> (or MPa or MN/m <sup>2</sup> )

**Table B.2** Conversion factors for density

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 Equivalent of 1 t/m<sup>3</sup> (or 1 Mg/m<sup>3</sup> or 1 g/cm<sup>3</sup>):
1000 kg/m<sup>3</sup>0.03613 lb/in<sup>3</sup>0.75237 UK ton/yd<sup>3</sup>0.8428 US ton/yd<sup>3</sup>62.43 lb/ft<sup>3</sup>


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**Table B.3** Conversion factors for force and weight

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 (a) Equivalent of 1 MN

1000 kN

10<sup>6</sup> N1.0196 × 10<sup>5</sup> kgf

100.4 ton f

2.248 × 10<sup>5</sup> lbf(b) Equivalent of 1 N/mm<sup>2</sup> (or 1 MN/m<sup>2</sup> or 1 MPa):1000 kN/m<sup>2</sup> (or kPa)10.197 kgf/cm<sup>2</sup>

10 bar

9.869 atm

102.2 m H<sub>2</sub>O355.2 ft H<sub>2</sub>O

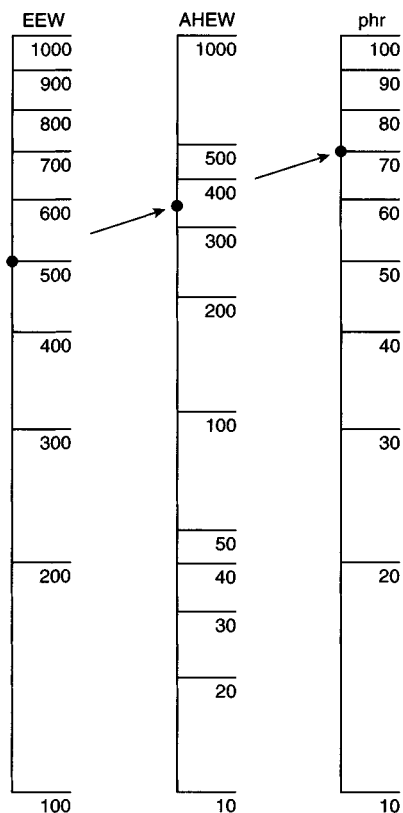
7500.6 mm Hg

9.320 ton/ft<sup>2</sup>145.04 psi (or lbf/in<sup>2</sup>)20886 lbf/ft<sup>2</sup>


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**Table B.4** Viscosity conversion table. Source: Dow Chemical Co., Midland, MI, USA

Standard poise	Gardner-Holdt tubes	Seconds		mPa s
		4 Ford cup	Gardner-Holdt	
0.50	A	20		50
0.65	B	26		65
0.85	C	34		85
1.00	D	40	1.46	100
1.25	E	46	1.83	125
1.40	F	51	2.05	140
1.65	G	57	2.42	165
1.80	G-H	60	2.64	180
2.00	H	65	2.93	200
2.25	I	75	3.30	225
2.50	J	85	3.67	250
2.75	K	96	4.03	275
3.00	L	108	4.40	300
3.20	M	117	4.70	320
3.40	N	123	5.00	340
3.70	O	127	5.40	370
4.00	P	131	5.80	400
4.35	Q	137	6.40	435
4.70	R	144	6.00	470
4.80	R+	147	7.03	480
5.00	S	154	7.30	500
5.50	T	166	8.10	550
6.27	U		9.20	627
8.00	U-V		11.60	800
8.84	V		13.00	884
10.70	W		15.70	1 070
12.90	X		18.90	1 280
14.40	X+		21.10	1 440
17.60	Y		25.80	1 740
22.70	Z		33.30	2 270
23.50	Z+		35.00	2 350
27.00	Z1		39.60	2 700
34.00	Z2		49.85	3 400
36.20	Z2+		53.10	3 620
46.30	Z3		67.90	4 630
62.00	Z4		91.00	6 200
63.40	Z4+		93.00	6 340
98.50	Z5		144.50	9 850
120.00	Z5+		176.41	12 000
148.00	Z6		217.10	14 800
200.00				20 000



**Figure B.1** Conversion monograph to find the quantity of hardener to be used with 100 parts of resin. Example illustrated: for resin DER 671, the epoxide equivalent weight (EEW) is approximately equal to 500; the amine hydrogen equivalent weight (AHEW) of the hardener (polyamide) is approximately 350; therefore, the suggested amount of curing agent to be used is 70 parts per 100 parts epoxy resin (phr). Reproduced with permission from Dow Chemical Co., Midland, MI, USA

## **Appendix C   Standards and standards organisations**

### **C.1   Addresses of some standard organisations**

American Society for Testing and Materials (ASTM)  
100 Barr Harbor Drive  
West Conshohocken  
PA 19428-2959  
USA

Telephone: +1-610-8329585  
Fax:           +1-610-8329555  
e-mail: [service@local.astm.org](mailto:service@local.astm.org)

British Standards Institution (BSI)  
Customer Services  
389 Chiswick High Road  
London W4 4AL  
UK

Telephone: +44-181-9967000  
Fax:           +44-181-9967001

In addition to British Standards the following standards are also obtainable from the BSI:

- DIN (German);
- EN (European);
- ISO (International);
- JIS (Japanese).



## **C.2 Standards**

### *C.2.1 Some useful testing standards*

#### *C.2.1.1 Adhesives*

##### *C.2.1.1.1 ISO*

ISO 4578: 1979 Adhesives: determination of peel resistance of high-strength adhesive bonds. Floating roller method.

ISO 4587: 1979 Determination of tensile lap-shear strength of high-strength adhesive bonds.

ISO 6237: 1987 Wood-to-wood adhesive bonds: determination of shear strength by tensile loading.

ISO 6238: 1987 Wood-to-wood adhesive bonds: determination of shear strength by compression loading.

ISO 6922: 1987 Determination of tensile strength of butt joints.

ISO 9653: 1991 Test method for shear impact strength of adhesive bond.

ISO/DIS 9664: 1993 Test methods for fatigue properties of structural adhesive in tensile shear.

##### *C.2.1.1.2 DIN*

DIN 54456:1989 Testing of structural adhesions. Test of resistance in climatic conditions.

##### *C.2.1.1.3 BS*

BS 5350 Methods of testing for adhesives: general introduction.

#### *C.2.1.2 Sealants*

##### *C.2.1.2.1 BS*

BS 4524: 1983 (1991) Specification for two-part polysulphide-based sealants (test methods included).

BS 5215: 1986 One-part gun-grade polysulphide-based sealants (AMD 548: 1986) (test methods included).

BS 5713: 1979 Specification for silicone-based building sealants.

BS 5889: 1989 Specification for one-part gun-grade silicone-base sealants (test methods included).

BS 6213: 1982 Guide to selection of constructional sealants (AMD 5466: 1987).

BS DD 69:1980 Method for classifying the movement capability of sealants.

BS DD 121: 1985 Classification system for sealants for building and construction.

*C.2.1.2.2 European Standards (EN)*

- EN 28339: 1990 Building construction: jointing products. Sealants: determination of tensile property.
- EN 28340: 1990 Building construction: jointing products. Sealants: determination of tensile properties at maintained extension (ISO 8340: 1984).
- EN 2839: 1990 Building construction: jointing products. Sealants: determination of extrudability of one-component sealants (ISO 8394: 1988).
- EN 29048: 1990 Building materials: jointing products. Determination of extrudability of sealants using standardised apparatus (ISO 9048: 1987).

*C.2.1.2.3 DIN*

- DIN 52 451 1983 Testing of building B sealants; determination of the change in volume after thermal stress; dipping and weighing method.
- DIN 52 452, part 1: 1981 Testing of building sealants; compatibility of sealants; compatibility with other building materials.
- DIN 52 452, part 2: 1981 Testing of building sealants; behaviour of sealants when exposed to chemicals.
- DIN 52 452, part 3: 1978 Testing of building sealants for sealing and glazing; compatibility of sealants with each other; compatibility of hardened and fresh sealants.
- DIN 52 453, part 1: 1978 Testing of sealants for sealing and glazing in building constructions; migration of binder; testing of discoloration of adjacent building materials.
- DIN 52 453, part 2: 1977 Testing of sealing compound for sealing and glazing in building constructions; migration of binder; paper filter method.
- DIN 52 453, part 3: 1977 Testing of sealing compounds for sealing and glazing in building constructions; migration of binder; testing of concrete discoloration.
- DIN 52 454: 1974 Testing of sealing compounds for sealing and glazing in building constructions; non-sag properties.
- DIN 52 455, part 1: 1975 Testing of sealing materials for sealing and glazing in building constructions; adhesion and cohesion test: pretreatment in controlled atmosphere and in water.
- DIN 52 455, part 1: 1982 Draft testing of sealing compounds in building constructions; adhesion and cohesion test; stress by standard atmosphere, water or higher temperatures.
- DIN 52 455, part 2: 1974 Testing of sealing and glazing compounds in building constructions; adhesion and extension test; cyclic conditions.
- DIN 52 455, part 2: 1982 Draft testing of sealing and glazing compounds in building constructions; adhesion and extension test; stress by water-heat cycling.

- DIN 52 455, part 3: 1974 Testing of materials for joint and glazing seals in building constructions: adhesion and extension test; exposure to light.
- DIN 52 455, part 4: 1977 Testing of sealing and glazing compounds for sealing and glazing compounds in building constructions: adhesion and extension test; extension and compressive cycle.
- DIN 52 455, part 4: 1982 Draft testing of sealing compounds for sealing and glazing in building constructions: adhesion and extension test; extension and compression cycles.
- DIN 52 456: 1976 Testing of sealing compounds for sealing and glazing in building constructions: determination of the extrudability of sealing compounds.
- DIN 52 458: 1975 Testing of sealing compounds for sealing and glazing in building constructions: determination of the recovery.
- DIN 52 459: 1981 Testing of building sealants; determination of the water absorption of backfill material; retentive capacity.

### *C.2.2 ASTM standards for sealants and waterproofing*

- C-920 Standard specification for joint sealants.
- C-510 Test method (TM) for staining and colour change of single or multi-component joint sealants.
- C-603 TM for extrusion rate and application life of elastomeric sealants.
- C-639 TM for rheological (flow) properties of elastomeric sealants.
- C-661 TM for indentation hardness of elastomeric type sealants by means of a durometer.
- C-679 TM for tack-free time of elastomeric sealants.
- C-719 TM for adhesion and cohesion of elastomeric joint sealants under cyclic movement (Hockman cycle).
- C-792 TM for effects of heat ageing on weight loss, cracking and chalking of elastomeric sealants.
- C-793 TM for effects of accelerated weathering of elastomeric joint sealants.
- C-794 TM for adhesion-in-peel of elastomeric joint sealants.
- C-962 Guide for use of elastomeric joint sealants.

#### *C.2.2.1 Latex sealants*

- C-834-91 Standard specification of latex sealants.
- C731 Test method (TM) for extrudability, after package ageing, of latex sealants.
- C-732 TM for ageing effects of artificial weathering on latex sealants.
- C-733 TM for volume shrinkage of latex sealants.
- C-734 TM for low-temperature flexibility of latex sealants.

C-736 TM for extension-recovery and adhesion of latex sealants.

D2202 TM for slump of sealants.

D2377 TM for tack-free time of caulking compounds and sealant.

#### *C.2.2.2 Waterproofing*

C-836-89 Standard specification for high-solids-content, cold-applied elastomeric waterproofing membrane for use with separate wearing course.

C-898 Guide for use of high-solids-content, cold-liquid-applied elastomeric waterproofing membrane with separate wearing course.

D-1191 Methods of testing concrete joint sealers.

#### *C.2.3 International standards (ISO)*

ISO 11600: 1993 Building construction: sealants – classification and requirements.

ISO 6927: 1981 Building construction: jointing – producing; sealants; vocabulary.

ISO 7389: 1987 Building construction: jointing product – determination of elastic recovery.

ISO 7390: 1987 Building construction: jointing products – determination of resistance to flow.

ISO 8339: 1984 Building construction: jointing products – sealant; determination of tensile properties.

ISO 8340: 1984 Building construction: jointing products – sealants; determination of tensile properties at constant temperature.

ISO 9046: 1987 Building construction: sealants – determination of adhesion and cohesion properties at constant temperature.

ISO 9047: 1989 Building construction: sealants – determination of adhesion and cohesion properties at variable temperatures.

ISO 10563: 1991 Building construction: sealants for joints – determination of change in mass and volume.

ISO 10590: 1991 Building construction: sealants – determination of adhesion and cohesion properties at maintained extension after immersion in water.

ISO 10591: 1991 Building construction: sealants – determination of adhesion and cohesion properties after immersion in water.

ISO 111431: 1993 Building construction: sealants – determination of adhesion and cohesion properties after exposure to artificial light through glass.

ISO 11432: 1992 Building construction: sealants – determination of resistance to compression.

### *C.2.4 ASTM tests for resin mortars, grouts and monolithic surfaces*

- C-413 Absorption of chemical resistant mortars, grouts and monolithic surfacing.
- C-466 Chemical resistance of mortars, grouts and monolithic surfacing
- C-579 Compressive strength of chemical-resistant mortars, grouts, monolithic surfacing and polymer concrete (based on resin, silicate, silica and sulphur binders).
- C-580 Flexural strength and modulus of elasticity on chemical-resistant mortars, grouts and monolithic surfacing.
- C-531 Linear shrinkage and coefficient of thermal expansion of chemical-resistant mortars, grouts and monolithic surfacing.
- C-307 Tensile strength of chemical-resistant mortars, grouts and monolithic surfaces.
- C-395 Chemical-resistant resin mortars.
- C-1170 Compressive creep of polymer machinery grouts.

### *C.2.5 BS tests for repair mortars, grouts and floorings*

- BS 6319, part 2 Compressive strength.
- BS 6319, part 3 Flexural strength.
- BS 6319, part 4 Slant shear test.
- BS 6319, part 7 Tensile strength.
- BS 8204, part 1 Impact resistance.

### *C.2.6 Coatings: miscellaneous test methods*

- ASTM D-4060 Abrasion resistance of organic coatings.
- DIN 1048 Resistance to positive water pressure.
- DIN 1048 Resistance to negative water pressure.
- ASTM D4541 Pull-off strength of coatings using portable adhesion tester.
- ASTM D1212 Wet film thickness of organic coatings.
- ASTM D1653 Moisture vapour transmission of organic coating film.
- ASTM D2794 Resistance of organic coatings to rapid deformation (impact test).
- ASTM D2248 Detergent-resistance: practice for organic coatings.
- ASTM D1735 Testing the water resistance of coatings using water-fog apparatus (practice).
- ASTM D523, BS 3900-D5 and DIN 67530 Measurement of gloss for coatings.
- ISO 6504, DIN 55984 Hiding power of coatings.
- ASTM D3363 Testing the scratch hardness of coatings.
- BS EN 2917: 1992 and ISO 9117: 1990 Measuring thorough drying time of coating.

ASTM D522 and BS 3900: E1 Cylindrical mandrel bend test.

ASTM D522, BS 900: E11 and ISO 6860 Conical mandrel test.

BS-5411, ASTM B499 and B244 and ISO 2178 and 2360 Measuring the coating thickness of ferrous and non-ferrous substrates.

ASTM D2354 and ISO 2115 Minimum film-forming temperature (MFFT).

Also, see Table C.1.

### *C.2.7 Selected Japanese Standards (in English)*

JIS K 6024: 1992 Epoxy injection adhesives for repair in buildings.

JIS K 6806: 1985 Water-based polymer-isocyanate adhesives for wood.

JIS K 6860: 1974 General recommended practices for atmospheric exposure of adhesive bonds.

**Table C.1** Coatings standards: DIN (German) and ASTM (US) norms. Source: Dow Chemical Co., Midland, MI, USA

Test method	DIN norm	ASTM norm	Other
Lap-shear strength	DIN 53 283, DIN 51 221	ASTM D-1002	
Tensile strength	DIN 53 455	ASTM D-638	
T-peel strength	DIN 53 282	ASTM D-1876	
Climbing drum peel strength	DIN 53 289	ASTM D-1781	
Static load	DIN 53 285		
Adhesive surface preparation	DIN 53 281		
Adhesion	DIN 53 151 (cross-cut) DIN 53 152 (conical mandrel)	ASTM D-2197	ASTM D-3359 (tape)
Chemical resistance		ASTM D-2248 (detergents)	
Edge coverage		ASTM D-2967	
Film thickness	DIN 50 981 (magnetic substrates) DIN 50 984 (non-magnetic substrates)	ASTM D-1005, D-1186 (magnetic substrates)	ASTM D-1400 (non-magnetic substrates)
Flexibility	DIN 53 152 (conical mandrel) DIN 53 156 (indentation)	ASTM D-1737 (cylindrical mandrel)	ASTM D-22 (conical mandrel) ASTM D01474 (indentation)
Heat deflection temperature	DIN 53 461	ASTM D-648	Martens
Flexural strength (N/mm <sup>2</sup> )	DIN 53 452	ASTM D-790	
Compressive strength	DIN 53 454	ASTM D-695	
Notched impact strength	DIN 53 453 (kJ/m <sup>2</sup> )		
Tensile shear strength on sand-blasted steel: speed of jaws = 10 mm/min	DIN 53 272 (N/mm <sup>2</sup> )		
Tensile strength at rupture			VSM 77101 (N/mm <sup>2</sup> )
Gloss	DIN 67 530 (reflection) DIN 53 159 (chalking resistance)	ASTM D-523 (specular)	
Heat resistance		ASTM D-2454 (overbake)	
Impact	DIN 53 453 (ball weight)	ASTM D-27094 (chip resistance)	ASTM D-3170
Weathering	DIN 53 159 (chalking) DIN 53 231 (UV-light)	DIN 53 166 (outdoor exposure)	ASTM D-659 (chalking) ASTM D-2246 (humidity and thermal cycling)
Blister resistance	DIN 53 209	ASTM D-714-56	

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